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# **RESEARCH ARTICLE**

# Thermal Optimization of a Radial Flux Permanent Magnet Synchronous Motor With Axial Division

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#### ABSTRACT

This paper proposes a method for thermal optimization for the radial flux permanent magnet synchronous motor (PMSM) used in light electric vehicles. Thermal effects cause many negative impacts, especially losses in electrical machines. These effects cause the permanent magnets to deteriorate and the motor to become inoperable in PMSMs. Therefore, it is important to optimize the operating internal temperatures of PMSM. In this study, it is suggested that the permanent magnets of the PMSM should be made in pieces in the axial direction in order to reduce the operating temperature value. The simulated design is a radial flux PMSM used in light electric vehicles with a power of 3.2 kW, 150 V, and 1000 rpm. ANSYS Electronics Desktop, a finite element method-based software, was used for electromagnetic field analysis, and ANSYS Motor-Cad software was used for thermal simulation. The simulation results show that the axial division of the permanent magnets reduces the PMSM internal temperature value.

Index Terms—Axial division of magnets, losses, permanent magnet synchronous motor, thermal analysis

#### I. INTRODUCTION

Permanent magnet synchronous motor (PMSM) has been used frequently in industrial applications and electric vehicles in recent years. At the same time, PMSMs are still in the process of development today. The PMSM is an electric motor which is light, small in size, highly efficient, long-lasting, has functional mobility, and can operate in the desired speed range [1]. These motors can reach the reference speed value in the shortest time during speed changes. In addition, the low torque fluctuation and noise have caused the usage areas to become widespread recently [2].

Today, many development studies are carried out on permanent magnets and ferromagnetic materials. These materials form the basis of PMSM structures. Researchers create different PMSM designs with the help of these developed materials. It has been presented in the literature by many researchers that the use of different variations of the design parameters of PMSM changes the efficiency, power, torque, and cost of the motor [1–4].

Electromagnetic simulation results are important to improve the performance of electric motors. Electromagnetic analysis results provide information about electric motor parameters. However, these

these results, thermal simulation results are also needed in PMSMs. Since the temperature of electric motors is inversely proportional to the magnetic flux, it directly affects the efficiency of the motor [5, 6]. Therefore, it is important to examine the time-dependent temperature change with thermal simulations in order for PMSM prototypes to achieve the desired results. The purpose of thermal analysis for electric motors is heat dissipation. Thus, the heat dissipation can be calculated and the regions determined as the heat source can be determined [7, 8].

results are not significant for realistic applications. In addition to

The PMSM is exposed to high thermal stresses during operation. Therefore, thermal simulation should be done before PMSM prototype production in order to reach the correct designs. The result of the analysis should be interpreted and the thermal effects should be calculated. Thermal effects can be minimized by both mechanical design changes and the selection of appropriate ferromagnetic materials [8]. Controlling the overheating of the PMSM with appropriate feeding techniques is another thermal optimization method. Thermal effects cause the motor to heat up and reduce the efficiency of the motor and reduce its life [9] and even cause the motor to malfunction and become inoperable.

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Thermal effects in PMSM also affect the loss of magnetic properties of permanent magnets. Reaching the maximum operating temperature of the permanent magnets, which is called the Curie temperature, causes the loss of their magnetic properties [8]. Thus, permanent magnet manufacturers offer these temperature values to users for each magnet. The temperature values on the magnets in the design can be determined with thermal simulation. Designers can choose the appropriate permanent magnet with this determined temperature value. Curie temperatures of magnets are important when choosing.

There are other factors besides the design factors that affect PMSM heating. The switching frequency of the motor and the related current has an effect. When the switching frequency of the power converter increases, the internal temperature of the motor rises due to the increase in losses [10]. It is also known that flux density affects temperature based on the analysis performed under various operating conditions [11].

There are different studies in the literature regarding the reduction of all these mentioned thermal increases. In these studies, mostly the method of variation of mechanical design parameters is used. In addition to mechanical designs, electric motor internal temperature values can be reduced with different cooling liquids and external cooling. However, these external methods are not preferred because they affect the manufacturing cost and require additional mechanical design and equipment. One of these methods is to prevent sudden heating of the motor by filling different types of stator slots with paraffin, which are specially created for the PMSM. As a result of various research, it has been revealed that winding temperatures can be increased or decreased by around 2°C by changing the thresholds of the motor current and the speed of the motor in relation to the reduction of the PMSM internal temperature [12].

Thermal optimization is very important for the motor's operating life for a high torque density PMSM. Thermal analysis of PMSM with heat pipe without changing the mechanical design is a method preferred by researchers. It is a method based on the transfer of motor winding temperatures with a heat pipe. It has been shown that winding temperatures can be reduced with this method. In addition, it was concluded that the operating time is longer than natural cooling [13].

The PMSM has been preferred in electric and light electric vehicles due to their superior properties in recent years. Many cities, which have targeted a sustainable environment and urban planning, encourage the use of electric and light electric vehicles. Torque ripple and thermal effects are important in brushless direct current motor [14] and PMSM. In this study, thermal simulation and thermal

#### **Main Points**

- Thermal optimization has been made for the Radial Intelligent Permanent Magnet Synchronous Motor (PMSM).
- Axial partitioning of radial flux motor is implemented.
- The internal temperature of PMSM has been reduced with split magnets.

optimization of a radial flux PMSM with 3.2 kW power, 150 V voltage, and 1000 rpm rated speed for use in a mini electric garbage collection truck are aimed. The most common methods in the literature for thermal optimization are changing the geometries of the PMSM or external cooling. A method was used without changing the geometry of the PMSM and not requiring an additional cost increase with the study. Thermal optimization is achieved by dividing the magnets of the PMSM, which has permanent magnets in the radial direction, in the axial direction. It is aimed to thermally improve the radial flux PMSM with this method. The outstanding feature of this study is that the thermal optimization of radial flux PMSM magnets by axial segmentation has not been found in the literature.

It is not very meaningful to make thermal simulations only to obtain the design parameters of electric motors. Therefore, it is more appropriate to extract the dynamic models of the designs and perform electromagnetic analyses before thermal analysis. Magnetic components were sized by analyzing them with the RMxprt package under ANSYS Electronics Desktop software. Electromagnetic analyses were performed with the Maxwell package of the same software. Afterward, thermal simulations were performed with ANSYS Motor-CAD software.

The importance of thermal effects in electric motors and the explanation of these effects are explained in the second part of the study. Electromagnetic field analyses of PMSM, which is preferred in radial flux in-wheel mini waste management garbage trucks, are shown in the third section. The thermal simulation is given in the fourth section. The optimization study is shown in the fifth section.

#### **II. THERMAL EFFECT**

The PMSMs heat up due to current and losses when exposed to the voltage required for operation. There is a difference between the ambient temperature of the motor and the temperature at the loading condition. This difference is described as the thermal effect in motors. The motor's ability to remove heat is directly proportional to its operating time at high power levels. Electric motors must transfer their internal heat by conduction or radiation. The performance, efficiency, and cost of the motor are positively affected by the development of the motor's ability to remove heat [14].

Overheating of the motor leads to malfunctions and burns in the motor. Overheating can have many causes. These are incorrect motor size, changes in load, extreme misalignment, hot ambient conditions, and phase-induced vibration and phase losses [15]. The heat generated by the effect of increasing temperature causes thermal stresses in the motor under load. If these stresses cannot be prevented, they may cause problems such as cage structure breakage in the motor body [16].

The uneven heating of the PMSM can disrupt the insulation of the motor. The deterioration of the insulation is usually caused by the motor windings. These windings become short-circuited without insulation. Thus, the motor winding wires are scorched and burned. At the same time, it causes demagnetization of the magnet and damages the mechanical elements [17]. Thermal increases due to overheating of the windings also affect permanent magnets. Each

permanent magnet has an operating temperature range. They deteriorate after a certain temperature. This limit temperature value is called the Curie temperature. Permanent magnets that reach the Curie temperature lose their magnetic properties. Therefore, it is important to know the motor operating temperature before production.

Heat sources cause heating in PMSM. Internal thermal sources of PMSM are copper, iron, and mechanical losses. Copper loss is the most important among these thermal sources. Copper losses result from heat dissipation due to ohmic resistance. The loss caused by copper losses constitutes approximately 96% of all losses [18]. The calculation of copper losses is shown in (1) [19].

$$P_{cu} = I^2 \times R \left[ W \right] \tag{1}$$

where *R* represents the internal resistance of the stator and *I* represents the motor current. The stator internal resistance is directly proportional to the temperature. Also, it is a large heat source [20]. Iron losses are divided into two types as Eddy current losses and Hysteresis losses. Eddy current loss is part of ferromagnetic losses caused by electromagnetic induction [19]. The expression of these losses is shown in (2).

$$P_{eddy} = K_g \cdot f^2 \cdot B_m^2 \left[ W \, / \, kg \right] \tag{2}$$

where  $K_{g}$  is the Eddy current loss coefficient of the material, f is the frequency of magnetic flux change, and  $B_{m}$  is the maximum intensity of the magnetic field.

Hysteresis losses are caused by the magnetization of the core as a result of the charging current. Its calculation is as in (3) [20–22].

$$P_{his} = K_h \cdot f \cdot B_m^{x} \left[ W / kg \right]$$
(3)

where  $K_h$  is the hysteresis loss coefficient of the material and x is the Steinmetz constant depending on the material.

Mechanical losses are losses due to friction. The impact of these losses is not very high. It is negligible in calculations compared to other losses. Stator internal resistance, material structures, frequency, and external effects can be used as calculation parameters affecting the temperature.

Electric motors can operate continuously at nominal power values. The rated power expression can be defined as the maximum shaft power with continuous operation. There may be short-term overloads on the motor shaft in some non-standard operating conditions. This situation, which is higher than the rated power value, has a disruptive effect on the electric motor. These effects are acceptable if the operating time is not long. Extending the operating time in case of overload can cause the motor windings to burn out due to heating, damage the winding insulators, and permanently lose the properties of the permanent magnets. The motor operating temperature value can also be kept under control with the control of the overload condition. The standard for thermal performance tests of electric motors is specified in IEC 600034-1. This standard covers various load cases and operating conditions. IEC 600034-1 is the international standard for the performance evaluations of rotary electrical machines.

The thermal analysis of the radial flux PMSM used in this article was performed with ANSYS Motor-CAD simulation software. ANSYS Motor-CAD software uses mesh networks similar to loop electrical circuit structures consisting of nodes. Thus, it reveals thermal problems and defines the thermal circuit model in a steady state. The software includes thermal resistors and heat sources connected between nodes of electric motor parts. In addition, this software also adds the thermal resistances of the object in the transient simulation model. Meanwhile, thermal capacitances are used to add the timevarying internal energy of the body to the calculations. The thermal resistances specified are calculated as conduction and diffusion as in (4) and (5) [20–22].

$$R_{cond} = \frac{l}{\lambda A} \tag{4}$$

$$R_{diff} = \frac{l}{\alpha A} \tag{5}$$

where *I* is the distance between the nodes,  $\lambda$  is the thermal conductivity coefficient, *A* is the cross-sectional area, and  $\alpha$  is the heat diffusion coefficient. The thermal capacitances are as in (6) [20–22].

$$C = V \rho c$$
 (6)

where V is the volume,  $\rho$  is the density, and c is the thermal capacity of the material [19].

#### **III. SIMULATION OF RADIAL FLUX PMSM**

A radial flux PMSM with a power of 3.2 kW, a voltage of 150 V, and a rated speed of 1000 rpm, used in the drive system of electric garbage collection vehicles, was determined. Garbage collection trucks that can work comfortably in narrow side streets in many districts of Istanbul, which have a sustainable and environmentally friendly urbanism, have turned into electric driven mini garbage collection trucks. These mini truck manufacturers, which are in the category of light electric vehicles, generally use PMSMs in the propulsion systems of these vehicles.

The PMSM, which is the subject of the study, is determined as radial flux and outer rotor. Outer rotor electric motors are known as inwheel electric motors. In-wheel PMSM is used in applications that do not require high power. In addition, this type of motor is ideal for small vehicles as it saves space. It is economical because it uses the power on the motor shaft without a drivetrain. The optimum solution for mini waste management garbage trucks, which are light electric vehicles, is the outer rotor structure. The values given in Table I were taken as the initial design parameters of the study. These parameters have been determined in accordance with the electric mini waste management garbage trucks currently in use, and the dimensional dimensioning of the motor has been created in accordance with these vehicles. Based on the parameters in Table I, simulations were carried out with the RMxprt package in ANSYS Electronics Desktop software to extract the dynamic model of the motor.

TABLE I. PMSM DESIGN PARAMETERS	
Parameter	Value
Power (kW)	3.2
Voltage (V)	150
Rated speed (min <sup>-1</sup> )	1000
Stator inner diameter (mm)	190
Rotor outer diameter (mm)	273
PMSM, permanent magnet synchronous motor.	

The most preferred materials in the literature are used as the rotor and stator materials of PMSM in the initial design. These materials, which are specified as the initial parameter, have received positive results from the researchers. Pre-simulation studies were carried out with these materials in order to reach the final design parameter. It was decided to use M19-26G as the stator material, Steel 1010 as the manufacturing steel for the rotor back iron, and NdFeB-38H as the permanent magnet as a result of the preliminary simulation study. The 24/18, 36/30, 36/26, and 24/20 models were analyzed in simulation studies to determine the appropriate slot/ pole number. According to the results of the simulation study, it is concluded that the 24/20 slot/pole number has the most efficient and suitable motor output values. Mechanical design parameters affect the output data of electric motors. One of the most important mechanical design parameters in PMSM is the slot structure. Simulations were made with ANSYS Electronics Desktop with different slot structures and dimensions. As a result, an optimized design was obtained. A similar determination was made for the magnet embrace ratio and the winding structure. The magnet embrace ratio was determined as 0.8. Single-layer winding has been chosen because it gives much better results as the motor winding structure of PMSM.

The slot occupancy rate has been determined not to exceed 60% with the specified parameters. This value is important for the placement of the motor windings without salient from the slot area. In addition, the resistance, self, and mutual inductance of all phase windings are equal and constant, magnetic circuit saturation is neglected and the motor's internal operating temperature value is determined as 90°C.

The ANSYS Electronics Desktop software RMxprt package simulation results performed after the design parameters are determined are shown in Table II.

It is seen in Table II that the simulated radial flux PMSM can operate at the target speed and torque value with the determined power value. One of the most important concepts in electric vehicles is range. Today, many research topics are on increasing the range of electric vehicles. One of the ways to increase the range is to use a high-efficiency electric motor. It is understood that the targeted efficiency value is satisfied due to the experimental value.

PMSM ANSYS RMXPRT SIMULATION RESULTS			
Parameter	Value		
Cogging torque (Nm)	0.6512		
Average input current (A)	22.9259		
Armature current density (A/mm <sup>2</sup> )	5.46578		
Total loss (W)	239.018		
Output power (W)	3199.87		
Input power (W)	3438.89		
Efficiency (%)	93.0496		
Rated speed (min <sup>-1</sup> )	1048.31		
Rated torque (Nm)	29.1484		
PMSM, permanent magnet synchronous motor.			

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Another parameter to be considered in electric motor designs is the armature current density. This value is expected to be between 4 and 6 A/mm<sup>2</sup>. An electric motor with an armature current density of more than 6 A/mm<sup>2</sup> needs an external cooling system. In-wheel electric motors are not suitable for external systems due to space constraints. Therefore, the design of these types of motors should not require external cooling. As seen in Table II, PMSM armature current density value is 5.46578 A/mm<sup>2</sup>. Accordingly, the proposed design is suitable for natural cooling.

The output torque change curve according to the speed change of the design simulated with the ANSYS Electronics Desktop RMxprt package is shown in Fig. 1. It is understood that the torque–speed curve of the PMSM is quite compatible with the targeted result. It has a torque of 29.1484 Nm at the target speed of 1000 rpm.

In order to be able to drive the mini waste garbage truck with PMSM, it must produce 3.2 kW of power at 1000 rpm. As a result of the simulation, it is seen that PMSM can produce this power at 1000 rpm. The change curve of the output power according to the motor speed is as in Fig. 2.









The efficiency–speed change curve of PMSM is as in Fig. 3. It is seen that the design has an efficiency of 93.05% at 1000 rpm, which is the motor speed.

Analytical solution results are not sufficient to evaluate the electric motor design results. The results of electromagnetic field analysis should also be examined. After the analysis with ANSYS Electronics Desktop RMXprt package, electromagnetic field simulation was done with Maxwell package under ANSYS Electronics Desktop software. According to the results obtained from both Table I and Figs 1–3, it is understood that the optimized design has been obtained. In order to verify these values obtained, PMSM's electromagnetic field analysis results should also support this.

Two-dimensional and three-dimensional electromagnetic simulations of the motor were carried out with the ANSYS Electronics Desktop software Maxwell package after it was concluded that the optimized design values were reached. Fig. 4 shows the two- and three-dimensional magnetic flux density distribution of the PMSM.

As seen in Fig. 4, the magnetic flux density does not reach the limit values. The near-saturated sections whose flux density is around 2.2 T are shown on the edges of teeth only. Also, as shown in Fig. 4, the flux exhibits a smooth and homogenous distribution as expected.

#### **IV. RADIAL FLUX PMSM THERMAL ANALYSIS**

The simulation results before the prototype production of electric motors are guiding for manufacturing. Electric motor output values and electromagnetic field analysis results obtained by the finite element method are important for electric motor design. These data should be supported by thermal simulation to create a realistic approximation. The thermal effect is a very important parameter for electric motor. Therefore, it is not possible to design an external cooling for the in-wheel PMSM. Since the outer body of the motor will be inside the tire, there cannot be a cooling design in the outer body. For these reasons, thermal simulation of radial flux PMSM design is important.

Thermal analysis results should be well understood. The distribution of thermal effects on the electric motor must be determined. Thus, the thermal values on the motor windings, permanent magnet, and stator are obtained. In this study, ANSYS Motor-CAD software was used for thermal simulation. ANSYS Motor-CAD creates a realistic approach as it models the operation of the electric motor. This software takes many data such as the geometric dimensions of the motor, electrical parameters, and magnetic field analysis results from the simulation file of the magnetic field analysis in order to perform thermal analysis. The collective parameter circuit model, which forms the basis of this software, is an analytical approach used to reveal the temperature effects of electric motors. Similar software that performs thermal analysis performs their analysis according to the stacks and their parameter circuit model. ANSYS Motor-CAD software calculates solutions with a thermal circuit model. The thermal model is like an electrical circuit. It contains the parts of the electric motor and their thermal parameters. The thermal circuit model determines the thermal effect by convection, conduction,



Fig. 4. Magnetic flux density distribution: (a) Two-dimensional; (b) Three-dimensional.

and radiation methods. The thermal values of these thermal spots interacting with each other are calculated by analytical methods. The thermal behavior of the stator and rotor is different from each other in the starting operation, continuous operation, and continuous overload situations in PMSM. Therefore, motor heating and cooling dynamics should be examined separately for the stator and rotor. Continuously operating rotor and stator thermal models should be combined. The thermal model for the stator and rotor is as in (7) and (8).

$$\Delta\Theta_{R} = \left[p_{R}\left(\frac{l}{l_{N}}\right)^{2}\Delta\Theta_{NR}\right]\left[1-e^{-t'_{1R}}\right] + \left[\left(1-p_{R}\right)\left(\frac{l}{l_{N}}\right)^{2}\Delta\Theta_{NR}\right]\left[1-e^{-t'_{2R}}\right]$$
(7)

$$\Delta\Theta_{s} = \left[p_{s}\left(\frac{l}{l_{N}}\right)^{2}\Delta\Theta_{Ns}\right]\left[1-e^{-t_{1s}}\right] + \left[\left(1-p_{s}\right)\left(\frac{l}{l_{N}}\right)^{2}\Delta\Theta_{Ns}\right]\left[1-e^{-t_{2s}}\right] \quad (8)$$

where  $\Delta \Theta_{o}$  is the thermal increase in the rotor,  $\Delta \Theta_{c}$  is the stator thermal increase,  $p_{\rm R}$  and  $p_{\rm S}$  are the weight factor for the short-time constant of the rotor and stator windings,  $I_{N}$  is the nominal current, I is the phase current,  $\tau_{\rm 1R}$  and  $\tau_{\rm 1S}$  is the instantaneous cooling-heating time constant of the rotor and stator windings,  $\Delta \Theta_{_{NR}}$  and  $\Delta \Theta_{_{NS}}$  give the thermal increase of the rotor and stator at nominal load and current state, time t, and  $\tau_{2R}$  and  $\tau_{2S}$  give the cooling-heating time constant in the rotor and stator body [21-25].

As a result of the thermal simulation made with ANSYS Motor-CAD, the overall thermal distribution on the PMSM is shown in Fig. 5.

The highest temperature region of the radial flux PMSM is 94.8°C in the stator windings as seen in Fig. 5. It is concluded that the lowest temperature region is the PMSM body with 65.1°C. According to the general thermal distribution, it is seen that the back iron temperature value is 65.1°C, the stator surface is 77.7°C, and the stator teeth are 77.9°C. The average temperature of the radial flux PMSM is 94°C.



Fig. 5. General thermal dissipation of the PMSM. PMSM, permanent magnet synchronous motor.

TABLE III. PMSM THERMAL ANALYSIS RESULT			
Temperature Zone	Temperature (°C)		
Housing	65.1		
Magnet surface	65.2		
Stator surface	77.9		
Winding (average)	94.0		
Back iron	65.1		
Bearing	77.4		
Shaft	77.4		
PMSM permanent magnet synchronous	motor		

It can be seen that the temperature on the permanent magnet is 69.2°C. It is known that the maximum operating temperature of the NdFeB-38H permanent magnet used in this design is 80°C. According to the thermal analysis results, it is seen that the magnet has not reached the maximum operating temperature. NdFeB-38H magnet does not reach Curie temperature. The permanent magnet is in the ideal operating temperature range. One of the PSMS thermal simulation results is that the magnets will not deteriorate

All thermal analysis data obtained by ANSYS Motor-CAD simulation are as in Table III.

The hottest area of the PMSM is around the motor windings. Although PMSM winding temperature is high, it is within acceptable limits. The stator and rotor steel materials selected for the prototype are materials that can operate within the temperature values specified in the thermal analysis results.

# **V. THERMAL OPTIMIZATION OF THE PMSM**

Two methods are generally used for the thermal optimization of conventional PMSMs. One of these methods is the mechanical design. The mechanical design method is based on two structures. The first step is increasing the contact surface of the motor with air. The second step is to remove heat from the motor. For this reason, most electric motors have cooling fins. The second method is the external cooling mechanism. The aim of the external cooling method is to increase the frequency of contact with air. In this way, cooling is aimed to be achieved without changing the surface dimensions. Both methods affect the production cost of PMSM.

Radial flux PMSMs with in-wheel structures do not have many options for thermal optimization. These thermal optimization methods are not preferred because of dimensional limitations. A new method has been created for this situation of radial flux PMSM, which is missing in the literature with the study.

Eddy current losses have an effect on the output values and especially the thermal values of the radial structured PMSM. It is known that



**Fig. 6.** Radial flux PMSM motor design with axial division. PMSM, permanent magnet synchronous motor.

with the decrease in eddy current paths, these losses will decrease. Thus, it is estimated that the heat distribution of the motor will improve. To reduce eddy current losses, the radial arrangement of magnets in the radial PMSM is divided into axial segmentation. This situation is seen in Fig. 6.

The new design, which is formed by dividing the permanent magnets forming the rotor into two parts in the axial direction, is given in Fig. 6. The new design is simulated with the parameters given in Table I. The result of the ANSYS Motor-CAD analysis of the PMSM in the axial segmented magnet structure is shown in Fig. 7.

The thermal distribution of PMSM has changed with the axially partitioned design. In particular, it changes in the magnet and its surroundings. The reduction in thermal effects on the magnet, motor windings, and their surroundings are given in Fig. 7. This decrease is approximately 1°C. The radial flux PMSM has been thermally optimized without dimensional changes and without any additional cost. The thermal change caused by dividing radially placed magnets in the axial direction is given in Fig. 8.



**Fig. 7.** General thermal dissipation of the segmented magnet PMSM. PMSM, permanent magnet synchronous motor.



**Fig. 8.** General thermal variation of the segmented PMSM in the axial direction. PMSM, permanent magnet synchronous motor.

#### **VI. CONCLUSION**

The thermal effect is one of the important parameters affecting the in-wheel PMSM performance. There are mechanical solutions such as adding propellers and fins to the body for cooling inside the body in standard electric motors with internal rotors. However, external cooling structures cannot be used in the in-wheel PMSM due to mechanical limitations. Therefore, it is necessary to analyze the thermal effects well before manufacturing. Thermal effects cause many negative effects, especially losses in electrical machines. These effects cause the permanent magnets to fail and the PMSM to become inoperable. The longer life cycle of the motor and less failure depend on thermal effects.

ANSYS Motor-CAD is thermal simulation software frequently used by researchers. It is used to analyze the thermal distribution of electric motors. In this study, thermal optimization of radial flux in-wheel PMSM was performed for a mini waste management garbage truck. The PMSM is frequently used in electric vehicles and industrial applications. It is recommended to partition the radial permanent magnets in the axial direction for in-wheel PMSM thermal optimization. The temperature in permanent magnets decreases from 65.2°C to 64.1°C with the axial division. The average temperature value of the motor windings, which is the section with the highest thermal effect, decreased from 94°C to 92.9°C. A decrease of approximately 1°C was obtained in the motor's internal temperature with the axial partition. The thermal reduction was achieved without any change in PMSM output values such as power, speed, and torque production. The thermal reduction obtained without changing the mechanical design is important as the production cost. Thus, thermal improvement was made without changing the motor geometry, using additional equipment and without additional costs. It is thought that the results obtained by dividing the magnets in the axial direction will be beneficial to the design process of hybrid and light electric vehicles. It supports the applications and productions for mass production on radial flux inwheel PMSMs. The production of PMSM is considered with these simulation data. The comparison of the performance test results of the prototype on the test bench with the simulation results will be shared with future studies.

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# **RESEARCH ARTICLE**

# A Digital Filter Design for Reactive Power Measurement

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#### ABSTRACT

The electric meters used to measure the amount of electricity consumption measure both active and reactive power consumption in the distribution line with current transformers. As in every analog measurement process, in every analog measurement, existing of undesired components such as noises, interferences and harmonics are caused mistakes. In order to remove this undesirable information included in the measurement from the measurement results, digital filters are used in applications because of their performance and their easily replaceable features. In this study, we aimed to remove unwanted components such as noise and interference from the measurement signal. The subject of a commercial project is to design a digital filter in MATLAB<sup>®</sup> environment, which allows filtering the measurements of reactive power consumption in power distribution lines with less than 1% error. To ensure whether designed filter satisfies for mentioned criteria or not, we used the Gaussian model as a noise model because Gauss noise is spreaded whole frequency spectrum. While the power signal modeled in the design is a sine wave of  $I_{pp} = 2 \text{ A } 50 \text{ Hz}$ , Gaussian noise with different variances and mean values is used in modeling the unwanted components.

Index Terms—Digital filters, digital signal processing, IIR, reactive power measurement

#### I. INTRODUCTION

Electric meter is used to calculate the electrical energy consumption. In order to determine the energy consumption, the voltage of the distribution line and the current drawn from the power distribution line need to be measured. Current transformers are used to measure information of the current drawn from the power distribution line. Because the current measurements are analog, the results obtained from the current transformer are converted into digital by the analog-digital converter units in the microcontroller and the consumption amount is calculated. As in every analog measurements processes, in every analog measurement, existing of undesired components such as noises, interferences and harmonics are caused to corruption on the measurement. In many analog measurement applications, it is used coupling capacitors to remove the DC components and, also use anti-aliasing filters to limit the frequency band of the measurement. But there are still noise, interference, and harmonic. Filters are used to remove these components from the measurement. Digital filters are basically of two types:

- 1. Infinite impulse response (IIR)
- 2. Finite impulse response (FIR)

The mathematical representation of these filters is shown below. The IIR filter equation is given in (1) and the FIR equation is given in (2).

 $y(n) = \sum_{k=0}^{N} b_{k} x(n-k) - \sum_{i=1}^{M} a_{k} y(n-i)$  (1)

$$y(n) = \sum_{k=0}^{N} b_k x(n-k)$$
(2)

There is a difference between the IIR and the FIR and its feedback mechanism. The IIR filter is a digital filter that has only feedback mechanism and this advantage give an ability to the IIR filter like to take the same filtered result in low filter order than the FIR filter.

There are many realization types of digital filters such as direct form-I, direct form-II, cascade, and parallel in literature. In this research, we used the direct form-I one because of its user-friendly usage. The illustration of this realization type for the IIR and the FIR is in Fig. 1 and Fig. 2, respectively.

In the literature review, the researchers who studied about the same field used six different filter design techniques to filter the measurements in power consumption. These are as follows:

- 1. Serial IIR low-pass filter [1],
- 2. IIR band-pass filter [2],

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Fig. 1. Realization of the IIR filter in direct form-I type. IIR, infinite impulse response.



Fig. 2. Realization of the FIR filter in direct form-I type. FIR, finite impulse response.

- 3. Parallel IIR low-pass filter [3],
- 4. Adaptive low pass filter [4],
- 5. IIR low-pass filter [5],
- 6. FIR low-pass filter with phase-orthogonal approach [6].

The common aspect of the studies is that the designed filters are run on either digital signal processing (DSP) microprocessors or field-programmable gate array. The cost of the designed filters is as important as their performance. Therefore, the designed digital filter is intended to work in a low-power microcontroller. Also, this filter will produce results with less than 1% probability of error.

When the measurement results are examined, the current value transferred from the power distribution line to the system is  $I_{pp} = 2.08$  A. As it is known, the city network is a 50 Hz sine wave. So, a 50 Hz sine wave was generated in MATLAB to model the measurement results and perform error analysis. A random number generating Gaussian noise was added to this generated sine wave. In the

# **Main Points**

- Current value transferred from distribution line to the system is peak to peak 2.08A.
- The city network is 50 Hz sine wave so that we set a model which is pure sine wave with peak to peak current value 2A.
- Also we used Gaussian noise as the noise model.
- To check the filters performance, we compared difference between unfiltered and filtered results.



other steps, the filtered and unfiltered results were compared and their compliance with the determined criteria was checked.

# II. GENERATION OF NOISE SIGNAL AND DESIGNING THE FILTERS

#### A. Generation of the Noise Signal

Power systems are 50 Hz sine wave in our country. Therefore, the system is modeled as 50 Hz sine. Gaussian noise model was used as a noise model because Gaussian noise is spreaded in whole frequency band as equally. Besides, where the noise power that we interested is not known where it is. For this reason, we used the Gaussian noise in our study as the noise model.

The outputs of the generated sine wave in the time and frequency domain are shown in Fig. 3 and Fig. 4, respectively.







Fig. 5. 50 Hz  $I_{_{PP}}$  = 2 A Sine wave with  $\sigma$  = 0.2,  $\mu$  = 0 Gaussian noise in time domain.

Gaussian noise has three parameters that can be changed. The amplitude, mean, and variance of Gaussian noise can be changed. In this study, only the mean value and the variant were emphasized. Gaussian noise with 0.2 variance and 0 mean was added to the sine wave. The result in the time domain is shown in Fig. 5, also the one in frequency domain is in Fig. 6.

The variance of Gaussian noise was fixed at 0.04, and at the same time, the mean value is increased to 2 to examine the DC component effect. Obtained results for the time domain and frequency domain are shown, respectively, in Fig. 7 and Fig. 8.

To have a deep understanding of the effect of the DC and the variance, as the DC was fixed at 2 and the variance is scaled up to 100.



Fig. 6. 50 Hz  $I_{\rm pp}$  = 2 A Sine wave with  $\sigma$  = 0.2,  $\mu$  = 0 Gaussian noise in frequency domain.



Fig. 7. 50 Hz  $I_{pp}$  = 2 A Sine wave with  $\sigma$  = 0.2,  $\mu$  = 2 Gaussian noise in time domain.

The time domain and the frequency domain are shown in Fig. 9 and Fig. 10, respectively.

Comparing the last eight figures (from Fig. 3 to Fig. 10):

- 1. Increasing the mean value of the Gaussian noise caused an increase in the DC level. The DC value is 13 dB bigger than the original value (Fig. 8).
- As that is known from probability, the Gaussian distribution is called the normal distribution. This is because the model affects the entire frequency domain equally. As explained, when the variance of the noise is increased, the generated noise is found to be approximately equal in the whole frequency domain.



Fig. 8. 50 Hz I  $_{\rm PP}$  = 2 A Sine wave with  $\sigma$  = 0.2,  $\mu$  = 2 Gaussian noise in frequency domain.



Fig. 9. 50 Hz  $I_{pp}$  = 2 A Sine wave with  $\sigma$  = 10,  $\mu$  = 2 Gaussian noise in time domain.



frequency domain.

3. As a result of the increase in the variance, the noise resembled the normal distribution (Fig. 10).

#### **B.** Designing the Filters

The DC component was assumed to be isolated when designing the filter. Thus, an undesirable important value was removed from the spectrum. As it is known, the Fourier transform of a sine signal is a unit impulse. The unit impulse is a theoretical signal whose amplitude is infinity and width 0. Since the model we designed is a sinusoidal filter, the filter must be a band-pass filter with a bandwidth close to 0 Hz and at least 50 dB attenuation to eliminate the noise (Fig. 8). The filter to be designed is intended to run on a low-power microcontroller. Therefore, it was predicted that it would be more appropriate to design an IIR filter because IIR filters have a feedback mechanism

[in (1)]. Unlike other filter types such as Elliptic, Chebyshev type I, Chebyshev type II, and the Butterworth filter will be an appropriate choice because the Butterworth filter does not generate oscillation in the pass band or in the stop band.

As a result of these filter requirements, the filters to be designed were selected Butterworth IIR band-pass filter. For this reason, four band-pass filters were designed in different orders and bandwidths. We used Bilinear Transform Method [7] to determine of the filters' orders and cutoff frequencies. Although the Bilinear Transform Method is briefly mentioned, further information is not provided here to avoid unnecessary lengthening of the paper. Let  $f_{c1}$  be lower cut-off frequency and  $f_{c2}$  be the higher cut-off frequency. Thus, the specifications of the designed filter are as follows:

- 1.  $f_{c1} = 49.5$  Hz,  $f_{c2} = 50.5$  Hz Butterworth IIR sixth-order bandpass filter,
- 2.  $f_{c1} = 49.8$  Hz,  $f_{c2} = 50.2$  Hz Butterworth IIR eighth-order bandpass filter,
- 3.  $f_{c1} = 49.9$  Hz,  $f_{c2} = 50.1$  Hz Butterworth IIR eighth-order bandpass filter,
- 4.  $f_{c1} = 49.85$  Hz,  $f_{c2} = 50.25$  Hz Butterworth IIR eighth-order bandpass filter.

The magnitude responses of these filters are shown in, respectively, Fig. 11.

#### **C. Simulation Results**

In the simulation, we assumed that isolation was provided between the measurement circuit and the microcontroller. So, the DC component was subtracted from the measurement results. For this reason, the Gaussian noise that was used as the model was set to a mean value of 0 and a variance value of 0.04. The noise model generated was included in  $I_{pp} = 2 \text{ A } 50 \text{ Hz}$  sine wave signal and the result is as obtained in Fig. 5.

The obtained result using the designed first filter is shown in Fig. 12.

The first filter can be considered to work as desired according to Fig. 12. There is just about 0.8% error, which is negligible. However, it was observed that there were oscillations in long-term output. The related figure is shown in Fig. 13.

If there is an oscillation in a system output, it may cause an unstable condition. In order to prevent the system from unstable conditions, we cannot use this filter. The output of the designed second filter is shown in Fig. 14(a). It is seen that the second filter partially provides the specified criteria.

It was used "partially" definition because there is about 1.7% error. This error is higher than the criteria. The output of the designed third filter is shown in Fig. 14(b).

According to Fig. 14(b), there is almost 41% fault. Therefore, it cannot be used. When the ten-period output of the designed fourth filter in Fig. 14(c) is examined, it is observed that it generates results with an error rate of 0.3%. The results meet the error rate criterion of 1%.







**Fig. 12.**  $f_{C1}$  = 49.5 Hz,  $f_{C2}$  = 50.5 Hz 6th Order IIR Butterworth bandpass filter output. IIR, infinite impulse response.

To make sure that the fourth filter is enough for this study, it plotted the long-term output and the results are obtained as in Fig. 15.

The results show that the fourth filter met the error rate criterion of 1%. According to the long-term filtering output in Fig. 15, a 2% overshoot and 3 seconds settling time are observed. Therefore, the designed fourth filter is preferred.





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**Fig. 14.** (a)  $f_{c1}$  = 49.8 Hz,  $f_{c2}$  = 50.2 Hz 8th Order IIR Butterworth band-pass filter output. IIR, infinite impulse response. (b)  $f_{c1}$  = 49.87 Hz,  $f_{c2}$ =50.17 Hz 8th Order IIR Butterworth bandpass filter output. IIR, infinite impulse response. (c)  $f_{c1}$  = 49.85 Hz,  $f_{c2}$ =50.25 Hz 8th Order IIR Butterworth bandpass filter output. IIR, infinite impulse response.



#### **III. CONCLUSION**

Considering the entire filters designed, it is seen that the first filter met the criteria, but it worked in an unstable state, the second filter designed had about 10% overshoot and it had a very long settling time, and the third filter had an error rate of 49%. According to the criteria determined for our system, the most suitable filter is the fourth filter because the error rate was very low and the settling time was very short. On the other hand, it was understood that the DC component should be removed from the filtering process. In Fig. 8, the power of the DC component is much more than the power of the signal. This will complicate the filtering process.

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# **RESEARCH ARTICLE**

# **Comparison of Level 2 Charging Topologies for Electric Vehicles**

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#### ABSTRACT

This article presents the charging status of electric vehicles by implementing two different charging topologies and demonstrates the comparison of power factor corrector (PFC) and Boost Cascaded by Buck-Boost (BoCBB) topologies. The former topology charger operates in boost mode, while the latter topology charger can operate in both modes (buck and boost) with a wide range of output voltage ranging from 30 V to 500 V. Moreover, using the harmonic modulation technique, former topology charger operation results in reduced total harmonic distortion, more efficiency, and high input power quality than the latter one. They are also evaluated on the basis of charging time, and by using PFC topology, the battery is charged to 5% in 10 min, while by using BoCBB the battery is charged to 3% in 10 min. The model's performance is verified by using MATLAB-Simulink.

Index Terms—Boost Cascaded by Buck-Boost, finite impulse response, pulse width modulation, proportional integral and derivative, synchronized pulse-width modulation

#### I. INTRODUCTION

Due to the combustion of oil and carbon dioxide emissions, environmental pollution is getting severe day by day, and alternative energy sources need to be utilized. Therefore, electric vehicles (EVs) or plugin hybrid electric vehicles (PHEVs) are becoming more popular nowadays and are the best option over conventional vehicles due to their high fuel price. IEEE, the Society of Automotive Engineers (SAE), and the Infrastructure Working Council (IWC) are preparing standards and codes for utility/customer interfaces [1].

Instead of charging EVs in public places, the level 2 chargers are the prime method of charging at home. These chargers are plugged into a 220 V outlet and are semi-fast chargers. The advantage of the level 2 charger is that it can be used as a bidirectional charger; i.e., it provides power from the EV to the grid when there are peak hours and from the grid to the EV for charging the battery. The preference for level 2 at private and public places is that it draws less power compared to the level 3 charger, which provides us fast charging at the cost of high load at grid network, sometimes causing overloading of a network [2].

Typically, these chargers have a power level of 3-7 kW [3-5]. The comparison of basic converter topologies based on self-power

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factor corrector (PFC) capabilities in the discontinuous mode of operation is discussed in [6]. Topologies based on bridgeless converters [7] and multilevel converters [8] are also reviewed. The limitation of the former converter is the significant degradation at low voltages, while the latter has a great number of passive components. Interleaved converters [9] and cascade converters [10] are also reviewed which not only have the advantage of high power factor and power quality but also have the disadvantage of cost and more stress on electrical components. Many controlled techniques like proportional integrator and proportional derivative in BoCBB have also been studied in [11] and [12]. Moreover, the Cuk converter [13] or Flyback converter [14] can also be used instead of buck-boost, but they have the disadvantage of high component sizes as they have inverting output voltages and cause minimum direct energy transfer which increases the stress on the components too. For high-voltage applications, single-switch buck-boost topology cannot be used and hence two-switch boost and buck topology are reviewed in [15] and [16]. This article aims to implement and compare the performance of level 2 chargers with improved power factor and efficiency by implementing two topologies. These topologies are compared on the basis of their charging time. The block diagram for these topologies is shown in Fig. 1.

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Fig. 1(a) shows an EV charger with PFC topology which consists of a two-stage converter one is the PFC stage that is followed by an isolated DC–DC converter. The PFC topology used has several advantages low cost, less stress on components, high efficiency, and a high power factor [3]. Fig. 1(b) demonstrates an EV charger with Boost Cascaded by Buck topology which consists of the rectifier and twoswitch buck-boost converter. An improvement in the power quality of the converter is made by a smooth transition provided by the alterable DC link between the two modes of operation: buck and boost.

Section II contains the description of topologies. Section III presents the methodology and simulation results of PFC study. Similarly, methodology and simulation results of BoCBB study are presented in Section IV and Section V presents conclusions.

#### **Main Points**

- After comparison, the power factor corrector (PFC) topology resulted in more power factor and reduced harmonic distortion, making it more efficient.
- The PFC topology takes 3–4 h for complete charging of battery, while the Boost Cascaded by Buck-Boost (BoCBB) takes 8–9 h in boost mode and 2–3 h in buck mode.
- Construction of PFC topology is less expensive and less complicated than BoCBB.
- PFC topology has fewer design calculations making it more reliable.

# II. REVIEW OF TOPOLOGIES A. Power Factor Corrector Topology

Electric vehicle supply equipment (EVSE) with PFC topology is composed of two stages, i.e., PFC and a DC-DC converter stage. The purpose of PFC is to improve power factor and reduce total harmonic distortion such that the rectifier takes the input of 220 V from the supply and rectifies it to 220 V DC and then the boost converter with diode  $D_s$  and switch  $S_s$  increases the voltage up to 400–450 V. The full bridge inverter converts the signal into AC controlled by uni-polar SPWM with a 20 kHz switching frequency. Four IGBTs are used with signals S1, S2, S3 and S4. These signals are obtained by comparing the saw-tooth with a 20 kHz normalized input signal and its phasereversed counterpart [17]. The output of the inverter is connected to a 1:1 galvanic isolation transformer. This transformer prevents unwanted current from flowing between these two isolated units. After that, the full bridge rectifier rectifies the signal which is filtered via a capacitor C<sub>2</sub> and will supply the desired value of current and voltage to the battery for charging [3]. The simulation circuit using PFC topology is shown in Fig. 2.

#### B. Boost Cascaded by Buck-Boost Topology

Boost Cascaded by Buck-Boost (BoCBB) topology is composed of two stages, i.e., DC–DC Boost Converter and DC–DC Buck Converter. This universal charger can address battery voltages of range 36–48 V, 72–150 V, and 200–450 V. The circuit consists of two switches,  $S_1$  and  $S_2$ . Single-switch circuit (Cuk or buck-boost) results in low efficiencies and high voltage and current stresses [13–16]. The circuit diagram of BoCBB is shown in Fig. 3.

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An AC supply of 230 V is applied to the full bridge rectifier which is converted into a DC of 230 V. Rectifier is connected with a boost converter with switches  $S_1$  and  $D_1$ , and it is followed by a buck converter with switch  $S_2$  and diode  $D_2$ . When the required output voltage ( $V_{out}$ ) needs to be greater than the input voltage ( $V_{in}$ ), the circuit must be operated in boost mode and in buck mode otherwise. For boost mode, a battery of 300 V and 500 Ah is connected across  $C_1$ , and for buck mode, a battery of 70 V and 20 Ah is connected across  $C_2$ .

For control implementation, FIR low-pass filter is connected at the output which is taken as feedback to block high-frequency voltage. After that PID controller is connected which is eliminating steady-state error. This error voltage is obtained by comparing the low-pass output voltage with the reference voltage which is fed to the PID controller [18]. In the buck mode duty cycle,  $S_{buck}$  will adjust the width of the pulse signal and  $S_{boost}$  will be zero at that time. Similarly, for boost mode  $S_{boost}$  is nonzero and  $S_{buck}$  is zero. A MATLAB Function (Fig. 4) is implemented which is comparing reference input voltage  $V_{in}$  with PID output voltage  $V_{out}$  (shown in Fig. 3) and provides a switching signal to  $S_1$  and  $S_2$  accordingly.

## III. POWER FACTOR CORRECTOR STUDY A. Methodology

Sub-operation modes are such that during positive half diodes  $D_2$  and  $D_3$  are on, while in negative half  $D_1$  and  $D_4$  are on, so that an output DC signal of 230 V is obtained. The boost PFC converter's main purpose is to rapidly flip the switch  $S_5$  in Fig. 2 on and off, i.e., when  $S_5$  is closed, the first state occurs  $L_1$  is energized by the rectifier causing the inductor current to increase. At the same time, diode  $D_5$  is reverse-biased (since its anode is connected to the ground via  $S_5$ ), and capacitor  $C_1$  powers the inverter circuit.

When  $S_s$  is open, the second state happens. In this stage, the inductor  $L_1$  de-energizes as it transfers energy to the load and recharges



	TABLE I.
F	ARAMETERS OF POWER FACTOR CORRECTOR TOPOLOGY
Daras	Poters Roost Mode

Parameters	Boost Mode
V <sub>in</sub>	230 V
f <sub>s</sub>	20 kHz
L <sub>1</sub>	1.25 mH
C <sub>1</sub>	2.17 uF
C <sub>2</sub>	2.17 uF
Power rating	3.45 kW
V <sub>out</sub>	320–400 V

the capacitor  $C_1$ . Cycling between the two states occurs at a high frequency in a way that keeps the output voltage constant while also controlling the average inductor current [19–20].

This PFC circuit gives an output range of 450V which serves as the input for the inverter circuit. When  $S_1$  and  $S_2$  are on the positive half of magnitude 380 V and  $S_3$  and  $S_4$  are on the negative half of magnitude 380V is obtained. The output of inverter circuit is given to the input of galvanic transformer (1:1) and the output of transformer which is 380V is connected with input of full bridge rectifier with diodes  $D_1$ ,  $D_2$ ,  $D_3$ , and D4 to produce output signal of 324V. Table I.

#### **B. Simulation Results**

It is pertinent to mention here that, in Fig. 2, 300 V, 500Ah battery is used.

After simulation, the voltage at the terminal of the boost converter in the PFC block is a DC signal boost up to 400–450 V. In Fig. 5, charging of the battery can be observed at the initial point as 1% whereas after 10 min it goes up to 6% approximately. It is also observed as the charging state of the battery gets higher the rate of charging gets slow as it is described in Table II.

Moreover, power quality is greatly affected by nonlinear load, i.e., the EV charger. This is because when charger is connected to the grid for charging purpose, harmonics and current-voltage fluctuations are produced. Electric vehicles with low SOC (state of charging) will have a great chance to produce harmonics. As a result, PFC topology has THD less than BoCBB topology. It can be measured by THD of voltage and current.





TABLE II.           COMPARISON OF PARAMATERS FOR BOTH TOPOLOGIES					
		BoCBB	BoCBB		
Parameters	PFC	Boost	Buck		
V <sub>out</sub>	324 V	324 V	78 V		
Charging time	3–4 h	8–9 h	1–2 h (20 AH)		
Efficiency	96%	94.43% 96.1%			
Battery charged in 10 Min					
Initial state 1%	6%	1.7%	7%		
Initial state 60%	61.6%	60.7%	61.4%		

$$THD_{\rm i} = \frac{\sqrt{\sum_{n=2}^{N} l_n^2}}{l_1} \times 100\%$$
(1)

$$THD_{v} = \frac{\sqrt{\sum_{n=2}^{N} V_{n}^{2}}}{V_{1}} \times 100\%$$
 (2)

#### IV. BOOST CASCADED BY BUCK-BOOST STUDY

## A. Methodology

The switches S<sub>1</sub> and S<sub>2</sub> are controlled by duty cycles that are given by

$$D_{\text{boost}} = \frac{\left(V_{\text{out}} - V_{\text{in}}\right)}{V_{\text{out}}}$$
(3)

$$D_{\text{buck}} = \frac{V_{\text{out}}}{V_{\text{in}}} \tag{4}$$

These switches alternate between the two states such that when  $S_1$  is on, and  $S_2$  is off, the charger operates in Boost mode while in the opposite case, the charger will operate in Buck mode. Output voltage after low-pass filtering is passed through PID after comparison with a reference voltage. Proportional integral and derivative signal and  $V_{in}$  are the parameters considered for the duty cycle. Pulse width modulation signal is generated on the basis of the duty cycle and the charger will operate in Buck or Boost mode after the comparison in MATLAB function. The calculated parameters of BoCBB are shown in Table III and their equations are as follows.

$$L_{\text{Boost}} = \frac{V_{\text{in}}}{2\Delta i_{\text{L}}} DT_{\text{s}}$$
(5)

$$C_{\text{Boost}} = \frac{l}{2\Delta V} DT_{\text{s}}$$
(6)

$$L_{\rm Buck} = \frac{V_{\rm in}D'}{2\Delta i_{\rm L}}DT_{\rm s} \tag{7}$$

$$C_{\text{Buck}} = \frac{V_{\text{in}}D'}{16\Delta VLf_{\text{s}}}DT_{\text{s}}$$
(8)

 TABLE III.

 PARAMETERS OF BOOST CASCADED BY BUCK-BOOST TOPOLOGY

Parameters	Buck and Boost Mode
V <sub>in</sub>	230 V
f <sub>s</sub>	20 kHz
L <sub>1</sub>	5.6 mH
L <sub>2</sub>	7.4 mH
C <sub>1</sub>	100 uF
C <sub>2</sub>	50 uF
Power rating	3 kW
V <sub>out (buck)</sub>	70–78 V
V <sub>out (boost)</sub>	320–400 V

Where D is the duty cycle,  $\Delta i_L$  is the average inductor current, D' = (1-D) and  $T_s = \frac{1}{\epsilon}$ .

Sub-operation modes are as, during positive half diodes  $D_3$  and  $D_6$  are on, while in negative half  $D_4$  and  $D_5$  are on, so that an output DC signal of 230 V is obtained. When  $S_1$  is closed,  $L_1$  is energized by the rectifier causing the inductor current to increase. At the same time, diode  $D_1$  is reverse-biased and capacitor  $C_1$  powers the battery to 324 V. When  $S_1$  is open,  $S_2$  is closed. In this stage, the inductor  $L_1$  de-energizes and recharges the capacitor  $C_1$ , while inductor  $L_2$  energizes as  $D_1$  becomes forward biased, and  $D_2$  becomes reverse biased, hence charging the battery to 78V.

#### **B. Simulation Results**

Following are the simulation results of the circuit shown in Fig. 3. The battery used for boost mode is 300 V and 500 Ah with an initial state of charge of 1% and charged for 10 min as shown in Fig. 6. The battery used for buck mode is 70 V and 20 Ah with the initial state of charge of 1%, i.e., shown in Fig. 7. This circuit is simulated for 10 min. The output voltage across the battery can be visualized as 324 V and 78 V in the case of Boost and Buck mode, respectively.

In Table II, a charging time comparison is presented at different initial states of the battery using different topologies. It is observed that when initially the battery is at 1% PFC topology requires 1 min 34 s,



**Fig. 6.** Charging of battery using Boost Cascaded by Buck-Boost topology in boost mode.





Buck Mode requires 1 min 30 sec, and Boost mode requires more than 15 min to charge a further 1% of the battery. Moreover, a comparison can only be made between the 500 Ah battery's charging with each other, whereas 70 V and 20 Ah battery has less capacity so they will get charged to a higher percentage in an interval compare to other batteries used in the simulation.

Power loss analysis greatly affects the efficiency of a charger. Total power dissipated will be the sum of power losses at each component, i.e., MOSFET, inductor, and diodes. Moreover, conduction losses are higher than switching losses. Efficiency decreases 3–5% as switching frequency increases. Efficiency is given by the equations:

$$Efficiency = \frac{P_{out}}{P_{in}}\%$$
(9)

#### **V. CONCLUSION**

In this article, level 2 EV Charger is implemented via PFC topology as well as BoCBB topology. Power factor corrector topology improves the power factor, reduces harmonics, and increases efficiency. By using PFC topology, the battery is charged up to 6% in 10 min while by using BoCBB battery is charged up to 1.7% and 7%, respectively, in boost and buck mode during 10 min with the initial state of battery at 1%. Power factor corrector topology is more efficient than that of BoCBB topology as the former takes 3–4 h for complete charging of the battery while the latter takes 8–9 h for a complete charge of battery charge mode, while for buck modes it takes 2–3 h for a charge.

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# **RESEARCH ARTICLE**

# Analysis of Photovoltaic System in Unbalanced Distribution Systems Considering Ambient Temperature and Inverter Efficiency

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#### ABSTRACT

This paper investigates the impacts of solar irradiance, ambient temperature, and solar inverter efficiency on the performance of a photovoltaic system. The analysis of the system has been performed on the unbalanced IEEE 13-node test feeder. The loads connected to the feeder are modeled as constant impedance, constant current, constant power (ZIP) loads, and the daily load profiles of three customers (commercial, industrial, and residential) are employed. A daily power flow simulation at 1-minute intervals has been carried out using Open Distribution System Simulator (OpenDSS). The PV system performance has been evaluated using numerical simulations under three weather conditions, namely sunny, semi-cloudy, and overcast. The results show that the PV system generates more power on sunny and semi-cloudy days while the PV output power is very low on an overcast day due to the extremely low solar irradiance. In addition, the energy demand from the substation and the power loss has been reduced with the deployment of the photovoltaic system into the distribution system. Moreover, when the ambient temperature and inverter efficiency are considered, the PV system produced more power in sunny and overcast conditions compared to when these factors are not taken into consideration or assumed the temperature is constant throughout the day. This result shows the effect of the temperature of the selected region on the performance of the PV system. The losses due to the inverter and temperature can be reduced by appropriately sizing the inverter and choosing a proper location with high solar irradiance and low temperature, respectively.

Index Terms—Ambient temperature, inverter efficiency, photovoltaic, power loss, unbalanced distribution systems

# I. INTRODUCTION

The impacts of climate change have been increasingly witnessed all over the world. Rising temperatures and drought frequency are affecting millions of people around the world. Regarding this, renewable energy sources such as solar are increasingly being used to meet energy needs and are seen as potential solutions to tackle serious energy crises and environmental concerns [1]. One of the most abundant renewable resources is solar energy, which is projected to be the fundamental basis for a sustainable energy economy. The power produced by a photovoltaic (PV) cell relies on several factors and these are categorized in [2] as follows: PV system, cost, installation, environmental, and miscellaneous factors. Several environmental factors such as shadows, dust, temperature, and solar radiation impact the PV system's output power. A significant factor of uncertainty that can complicate energy planning and jeopardize investment opportunities in the power industry is the vulnerability of PV systems to future climate patterns. The impacts of extreme weather and climatic conditions on PV power outputs have been studied in [3]. Higher temperatures and persistent cloud cover reduce the output power of the

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PV system. Power electronics are also a crucial part of PV production. Several power converter topologies and power tracking methods have been proposed in [4]. The efficiency of PV inverters has increased over time and achieved values over 97% [5]. The thermal behavior of PV systems has been studied recently in [6, 7]. The open circuit voltage is significantly impacted by the rise in cell temperature; it decreases linearly with rising cell temperature. The PV output power relies on solar insolation that can fluctuate significantly as clouds pass overhead. Unless appropriate measures are taken, this can result in significant negative power quality at high-level penetrations [8]. Historically, the distribution system was planned based on peak demand. With the proliferation of distributed resources such as PV, it has become crucial for grid planners to analyze and design for dynamic conditions [9]. Therefore, it is essential to accurately predict PV power output under real weather conditions. The impact of voltage fluctuations due to the moving cloud shadows on the distribution system with high PV penetration is assessed in [10]. The impact of temperature and irradiance on key parameters of various PV cell types was investigated in [11]. Furthermore, several studies on the impact of PV penetration on

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Content of this journal is licensed under a Creative Commons Attribution-NonCommercial 4.0 International License. the distribution network have been carried out. Mohanty et al. investigated the impact of PV penetration on an unbalanced distribution network with dynamic load conditions [12]. Results reveal that loss occurs comparatively less in buses with capacitors and more in buses without capacitors. Additionally, the voltage profile remained within the desired range and the PV injection has not resulted in an abrupt increase or decrease in bus voltages. Moreover, Radatz et al. assessed various distributed generation penetration levels in a real distribution feeder [9]. These studies, however, have not examined the impact of PV systems on distribution networks when ambient temperature and inverter efficiency are taken into account. This is why this study has been carried out. The contribution of this paper is to analyze the impact of PV systems on distribution networks considering the temperature and inverter efficiency using three load profiles and three solar irradiance data with 1-minute resolution.

In this paper, an accurate simulation of the effect of PV on the distribution network is investigated by considering temperature, solar irradiance, and inverter efficiency parameters. For that purpose, a 1-minute step size simulation is carried out on Institute of Electrical and Electronics Engineers (IEEE) 13-node system using Open Distribution System Simulator (OpenDSS) [13]. Three weather conditions which are sunny, semi-cloudy, and overcast have been used to analyze the PV system. Moreover, the analysis of the PV system has been conducted by considering ambient temperature and inverter efficiency as these affect the output of the PV system. Then, the effect of ambient temperature and inverter efficiency on the PV system's output has also been demonstrated by comparing it with the PV system case which considers only the solar irradiance. Following this introductory part, the distribution network and the voltage-dependent load model (ZIP) used in this study are explained in Section II. In section III, the study location and the data of irradiance, temperature, and inverter efficiency, as well as the modeling of the PV array and the inverter element in OpenDSS are presented. Finally, case studies and simulation results are presented in Section IV and the conclusion is given in Section V.

#### II. DISTRIBUTION NETWORK DESIGN A. IEEE 13-Node Radial Distribution Feeder

The IEEE 13-node test feeder has been used in this study to evaluate the PV system's impact on an unbalanced distribution system. The

# **Main Points**

- The effect of solar irradiance, ambient temperature, and inverter efficiency on the photovoltaic (PV) system in unbalanced distribution systems has been investigated by using OpenDSS.
- A daily power flow simulation with a 1-minute step size has been performed to evaluate the effect of short-term PV fluctuation on the distribution system.
- Three irradiance curves representing sunny, semi-cloudy, and overcast weather conditions have been considered.
- Three case studies have been conducted to assess the impact of PV integration into the distribution network.
- By integrating PV into the network, the power loss and the power drawn by the substation have been reduced.

IEEE 13-node test feeder is characterized by the type of load (spot and distributed loads), line types (single-/three-phase overhead and underground lines), voltage regulators, shunt capacitors, and transformers. The voltage regulator operates based on line drop compensation. The data about the system are explained in [14]. This system has total active and reactive power loads of 3466 kW and 2102 kVAr, respectively. The single-line diagram for the modified test feeder is represented in Fig. 1.

# **B. Load Modeling**

Two main approaches have been traditionally used to develop load models: the component-based approach and the measured-based approach [15]. The component-based approach relies on knowledge of the individual components that make up the load while the measured-based approach is based on how the load behaves when subjected to voltage variations [15]. The load selection criteria depend on the type of analysis performed and the load's characteristics. In the steady state power flow studies, loads can be modeled as static. One of the most common static load models is the second-order polynomial load model, composed of constant impedance, current, and power characteristics. The static model is also known as the ZIP model [16].

Table I shows the ZIP coefficients [17] for commercial, residential, and industrial customer classes and the nodes at which the loads are connected. The active and reactive power of the ZIP coefficients model is given in (1) and (2).

$$P = P_0 \left[ Z_{\rho} \left( \frac{V}{V_0} \right)^2 + I_{\rho} \frac{V}{V_0} + P_{\rho} \right]$$
(1)

$$Q = Q_0 \left[ Z_q \left( \frac{V}{V_0} \right)^2 + I_q \frac{V}{V_0} + P_q \right]$$
(2)





		ZIP COEFFICI	ENTS AND TH	<b>TABLE I.</b> HE NODES OF I	DIFFERENT LOA	D TYPES [4]	
Class	Z <sub>P</sub>	I <sub>p</sub>	<b>P</b> <sub>p</sub>	$Z_q$	I <sub>q</sub>	P <sub>q</sub>	Load Nodes
Residential	0.85	-1.12	1.27	10.96	-18.73	8.77	671-634-652-611
Commercial	0.43	-0.06	0.63	4.06	-6.65	3.59	692-645-646
Industrial	0	0	1	0	0	1	670-675



The load shapes presented in Fig. 2 show 24-hour normalized load shapes for residential, commercial, and industrial customers and are taken from [17]. One can deduce that the peak power demand varies depending on the type of customers.

#### **III. PHOTOVOLTAIC SYSTEM MODELING**

The model of the PV system in OpenDSS is a combination of the PV array and the PV inverter which is useful for distribution system studies [18]. The block diagram of the model has been depicted in Fig. 3.

#### A. Irradiation Curves and Temperature

The output power of PV plants is intermittent and heavily relies on the weather condition and the time of day. Days with clouds or rain cause significant fluctuations in PV power output [19]. In this study, the impact of three solar irradiances on the output of PV production has been analyzed. The datasets used have been retrieved from a network composed of 24 irradiance sensors measuring solar irradiance (global horizontal irradiance, W/m<sup>2</sup>) in Alderville (Ontario) [20]. These datasets correspond to three categories: clear-sky(sunny), overcast, and variable(semi-cloudy) days. The solar irradiance has been measured on 2015-03-24 for clear sky, 2015-02-08 for overcast, and 2015-10-08 for semi-cloudy. Each dataset is defined as a 1-minute step size for 24-hour period making a total of 1440 data. The selected location for the study has a latitude of 44.190159 (°) and a longitude of -78.096701(°). The three irradiation curves are shown in Fig. 4.

Three temperature data for sunny, semi-cloudy, and overcast conditions have been obtained in this study. The data consist of 1-minute intervals for 24 hours corresponding to the same days of the



Fig. 3. Photovoltaic system model in OpenDSS [9].

previously mentioned solar irradiance data has been. The temperature data were originally obtained as ambient temperature (Fig. 5) from the National Aeronautics and Space Administration (NASA) Langley Research Center Prediction of Worldwide Energy Resource Project funded through the NASA Earth Science/Applied Science Program [21]. However, in OpenDSS, the PV element model



Fig. 4. Irradiation curves for sunny, semi-cloudy, and overcast days.



Fig. 5. Ambient temperature for sunny, semi-cloudy, and overcast days.

uses panel temperature ( $T_c$ ). Therefore, the  $T_c$  has been calculated using (3) presented in [22]. The wind effect is not considered in the equation.

$$T_{c} = T_{a} + \left(\frac{T_{NOCT} - T_{a,NOCT}}{G_{NOCT}}\right)G_{T}$$
(3)

where the  $T_c$  is the cell temperature,  $T_o$  is the ambient temperature,  $T_{NOCT}$  is the nominal operating cell temperature (NOCT) (43°C was taken in this study ),  $T_{a,NOCT}$  is the ambient temperature considered for NOCT conditions (20°C),  $G_T$  is the plane module irradiance, and  $G_{NOCT}$  is the solar irradiance for NOCT condition (800 W/m<sup>2</sup>). The PV panel temperature at the selected location with the ambient temperature given in Fig. 5 is shown in Fig. 6.



#### **B. Photovoltaic Array**

The PV element is connected to node 680 of the IEEE 13-node test feeder as shown in Fig. 1. In OpenDSS, for the model to calculate the output power of the PV array (*panelKW*), it requires the data of irradiance, temperature (*T*) factor, and rated power of the panel at the maximum power point ( $P_{mpp}$ ) defined at 1 kW/m<sup>2</sup> irradiance and a constant panel temperature (25 °C) [18]. The  $P_{mpp}$  of the PV array has been chosen to be 1000 kW with a power factor of 1. The maximum power output of the panel is calculated using (4).

#### $P(panelKW) = P_{mpp} \times irradience \times factor(@ actualT)$ (4)

The temperature coefficient affects the power output of PV panels and the power output of the PV decreases linearly as the temperature increases. The panel output is then reduced by a factor based on the temperature of the panel. The power versus temperature curve shown in Fig. 7 is defined using (5). The power decreases by about 18% as the panel temperature rises from 25 °C to 85 °C. In this study, the manufacturer datasheet of the AS-MQ7-156 HC solar PV module has been used. The temperature coefficient from the datasheet has been taken into account to calculate the maximum power produced by the PV at various irradiances and temperatures using the equation given in (5) [12].

$$P_{\max} = P_{\max(STC)} \frac{G}{1000} \left[ 1 + TC \left( P_{\max}, G \right) \left( T_C - 25 \right) \right]$$
(5)

where  $P_{max(STC)}$  is the maximum power of the photovoltaic cell at Standard Test Condition (600 W), *G* is the solar irradiance (1000 W/m<sup>2</sup>),  $T_c$  is the temperature of the photovoltaic cells, and TC ( $P_{max}$ , *G*) is the temperature coefficient for the at irradiance G ( $-0.36\%/^{\circ}C$ ). The relationship of the  $P_{mpp}$ -temperature curve for a PV panel rated power in 1 pu at 25°C is shown in Fig. 7.

#### C. Inverter Efficiency Curve and Optimum Inverter Sizing

The DC power produced by the PV panel must be converted to AC power by solar inverters to be injected into the grid. In this work, a mathematical method presented in [23] has been used to determine the optimum inverter size. The equation for selecting the optimum inverter output power is presented in (6):







Fig. 8. The efficiency curves of different solar inverters. (a) Solar Konzept, 2 kW; (b) Sunways, 3.6 kW; (c) SMA, 5 kW; (d) SMA, 11 kW; (e) Satcon, 50 kW; (f) Satcon, 100 kW; (g) Siemens, 1000 kVA [22].

	TABLE II. CASE SCENAF	RIOS	
	Scenario	Connection	1
Case		Generator	PV
BASECASE		×	×
GENCASE	Sunny	<i>✓</i>	×
	Cloudy	<i>✓</i>	×
	Overcast	1	×
PVCASE	Sunny	×	1
	Cloudy	×	1
	Overcast	×	1

× stands for: there is no connection.

where B and C parameters are determined from the efficiency curves of the inverter shown in Fig. 8, and the  $P_{max}$  is the highest produced power from the panel. In this work, the maximum DC power output of the PV is 785 kW. As a result, an optimal size of 1330 kVA rated inverter has been selected using the B and C parameters of Siemens 1000 kVA inverter presented in [23]. In OpenDSS, the inverter model

finds the mpp within the simulation time step. The efficiency curve of various inverters is shown in Fig. 8.

#### **IV. RESULTS**

In this work, the daily mode simulation has been performed using the OpenDSS software [13]. This mode calculates the power flow for a period of 24 hours. A total number of 1440 power flow simulations have been performed considering a 1-minute interval. Three cases are designed to evaluate the impact of PV penetration into the grid: the BASECASE, the GENCASE, and the PVCASE. Both GENCASE and PVCASE have three scenarios namely: sunny, semi-cloudy, and overcast. The case scenarios are summarized in Table II.

The BASECASE is the case in which the simulation is conducted on the original IEEE 13-node test system with no PV. The results of this case are then recorded to compare with the other two cases. In the second case (GENCASE), a 1000 kW generator is connected to node 680 to evaluate the distribution network. The generator element in OpenDSS can be modeled with the consideration of daily solar irradiation without the temperature effect. In this case, it is assumed that the generator behaves as a PV system without considering the effect of the temperature variation (assuming it is constant at 25°C during the day) and the inverter efficiency. Therefore, three daily irradiance curves (sunny, semi-cloudy, and overcast) are used to model the generator. Case 3 is the PVCASE in which the PV is connected to node 680. In this case, the inverter efficiency and the panel temperature are taken into account to assess the impact of the PV system on the distribution systems. The three irradiance and temperature curves are used to model the PV element.

Table III compares the daily simulation results obtained from the BASECASE and the three GENCASE scenarios (sunny, semi-cloudy, and overcast). The total energy generated is equal to the sum of the energy consumed by the load and the energy loss in both cases, as illustrated in the table. For GENCASE, the generated power at node 680 is the highest during the GENCASE(sunny) at 5859 kWh followed by the GENCASE(semi-cloudy) and GENCASE(overcast) at 4155 kWh and 531 kWh, respectively. The energy losses of the feeder and substation demand have also been reduced for the three GENCASE scenarios when compared to the BASECASE. The greatest energy loss reduction is 19.44% for GENCASE(sunny), followed by 14.31% and 2.01% for GENCASE(semi-cloudy) and GENCASE(overcast), respectively. Figs. 9, 10, 11 and 12 show the daily active power flowing through the substation for BASECASE and GENCASE scenarios.

TABLE III.           COMPARISON BETWEEN BASECASE AND GENCASE					
Various Cases	Energy Measured at Substation (kWh)	Energy Measured at Node 680 (kWh)	Energy Consumed by the Loads (kWh)	Energy Losses of the Network (kWh)	Energy Loss Reduction (%)
BASECASE	52 664	-	51 574	1090	
GENCASE(sunny)	46 570	5859	51 551	878	19.44%
GENCASE(semi-cloudy)	48 378	4155	51 599	934	14.31%
GENCASE(overcast)	52 117	531	51 580	1068	2.01%

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Fig. 10. Power in each phase at the substation for GENCASE (sunny).



Fig. 11. Power in each phase at the substation for GENCASE (semi-cloudy).



Fig. 12. Power in each phase at the substation for GENCASE (overcast).



Fig. 13. Power in each phase at the substation for PVCASE (sunny).



Fig. 14. Power in each phase at the substation for PVCASE (semi-cloudy).

TABLE IV.           COMPARISON BETWEEN BASECASE AND PVCASE					
CASE	Energy Measured at Substation (kWh)	Energy Measured at Node 680	Energy Consumed by the Loads (kWh)	Energy Losses (kWh)	Loss Reduction
BASECASE	52 664	-	51 574	1090	
PVCASE(sunny)	46 501	5926	51 552	875	19.72%
PVCASE(semi-cloudy)	48 500	4037	51 599	938	13.94%
PVCASE(overcast)	52 059	587	51 580	1066	2.2%

The total energy generated, energy consumed, and energy losses for BASECASE and PVCASE are presented in Table IV. The energy demand from the substation and the energy losses of the network have been reduced for all the PVCASE scenarios. The highest energy loss reduction is achieved in PVCASE(sunny) at 19.72% compared to the PVCASE(semi-cloudy) at 13.94% and PVCASE(overcast) at 2.2%. The daily active power flow through the substation for PVCASE is given in Figs. 13, 14 and 15.



Fig. 15. Power in each phase at the substation for PVGENCASE (overcast).

	TABLE V.
COMPARISON	BETWEEN PVCASE AND GENCASE

Scenario	Daily PV Panel Energy Output (kWh)	Energy Measured at Node 680 for PVCASE (kWh)	Energy Measured at Node 680 for GENCASE (kWh)	Energy Difference Between PV Output and PVCASE (kWh)
Sunny	6044	5926	5859	118
Semi-cloudy	4118	4037	4155	81
Overcast	600	587	531	13

The comparison between the energy measured in PVCASE, GENCASE, and PV panel output is presented in Table V. When the effect of inverter efficiency and temperature is not taken into account in GENCASE, the energy measured is 5859 kWh for sunny, 4155 kWh for semi-cloudy, and 531 kWh for overcast. When the temperature effect alone is considered, the energy measured at the PV output has increased for sunny and overcast conditions by 3.06% and 11.5%, respectively, compared to GENCASE. However, for semi-cloudy weather, the PV energy output has decreased by 0.9%. This is because the temperature in the selected region is below 25°C on sunny and overcast days, but above 25°C on semi-cloudy days. This result shows the impact of temperature on PV power output.

The difference between the energy output of the PV and the energy measured at node 680 for PVCASE is 118 kWh for sunny weather, 81 kWh for cloudy weather, and 13 kWh for overcast weather. These energy differences are due to the inverter loss. Because the inverter used in the study has high efficiency (see Section III), the energy losses caused by the inverter are relatively low. These losses would have been greater if a lower efficiency inverter had been chosen. This result emphasizes the significance of selecting an appropriate inverter.

#### **V. CONCLUSION**

This paper assesses the impact of a PV system on unbalanced distribution power systems considering temperature, irradiance, and inverter efficiency. The study has been tested on the IEEE 13-node test feeder with a ZIP load model and different customer types using OpenDSS. The daily simulation mode has been conducted on three different case scenarios. The results indicate that when the effect of temperature alone is considered, the PV panel produced more energy by 3.06%, and 11.5% for PVCASE (sunny) and PVCASE (overcast), respectively, compared to GENCASE scenarios. However, when the impact of both the inverter and temperature is taken into account, the injected power to the grid has decreased to 1.95% and 2.16% for PVCASE (sunny) and PVCASE (overcast), respectively. By connecting the PV to the network, energy losses and energy demand from the substation are reduced. Moreover, it has been observed that the efficiency of the selected inverter and the ambient temperature affect the amount of power injected by the PV system. Therefore, it is concluded that the weather conditions of the PV site and the inverter selection should be considered during PV system integration into the distribution systems.

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# **RESEARCH ARTICLE**

# Design and Implementation of a Power Supply for KNX Protocol

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#### ABSTRACT

KNX is a widely used organization in the world that standardizes the open system communication protocol for smart home and building automation. KNX controls integrated functions such as heating, cooling, ventilation, lighting systems, audio and video services, security, and energy management in all types of residential, commercial, and industrial building structures. KNX power supply is designed to ensure the continuous operation of these automation systems by considering the number of devices connected to the system. According to the KNX standards, in devices that are compliant with these standards, the main current and communication signals required for the operation of the devices use the same line. Conventional power supplies cannot cope with these standards and therefore special power supplies are required. In this study, a high-frequency (100 kHz) and high-efficiency (minimum 85%) flyback converter-based power supply with 155–265 *V*<sub>ac</sub> input and 30 V 640 mA output values in accordance with KNX standards has been designed and implemented.

Index Terms—DCM operation, flyback converter, KNX power supply

#### I. INTRODUCTION

The KNX protocol has emerged with the combination of European Installation Bus (EIB), European Home Systems (EHS), and Batibus protocols which are developed by the leading automation companies in Europe. Batibus is widely used in Italy, Spain, and France, while EIB is widely used in Germany, German-speaking countries, and Northern Europe. EHS is preferred by digital household and electronic device manufacturers. Nowadays, devices that are compliant with KNX are widely used in many countries of the world and they are under the supervision of the KNX organization [1–9].

The KNX protocol is open source, can be easily integrated into different systems, requires minimal maintenance, and is a problem-free system. For this reason, it is preferred in many projects in industrial and commercial applications. In a project prepared with the KNX protocol, many different brands and product groups that support this protocol can be used together without being dependent on a single manufacturer and brand [2–5].

Nowadays, with the development of technology, the usage of devices that make our daily lives easier and energy consumption have increased. In smart home and building systems, various automation systems are used to meet heating, cooling, lighting, energy management, and other user requirements in terms of both comfort

and efficient energy use. KNX organization is widely used in these systems due to its advantages [6–8].

According to the standards of the KNX protocol, in devices connected to this protocol, the main current required for the operation of the device and the communication signals use the same line. Conventional power supplies cannot cope with these standards and therefore special power supplies are required. For this purpose, the KNX power supplies are designed to operate under a wide input range and 30  $V_{dc}$  output voltage. It provides both power and communication transfer on the same line. An integrated choke is used to separate the power supply and communication signals [4–9].

In this paper, a high frequency (100 kHz), high efficiency (minimum 85%) flyback converter-based KNX power supply with 30  $V_{dc}$  output voltage and 640 mA nominal output current, 155–265  $V_{AC}$  input voltage range has been designed and implemented. The losses are reduced and efficiency is increased by using proper snubber cells.

#### II. FLYBACK CONVERTER

The conventional flyback converter circuit scheme is given in Fig. 1. In this figure,  $V_{dc}$  is the input voltage,  $I_p$  is the primary current,  $I_s$  is the secondary current, Q is the switch, D is the diode,  $L_p$  is the primary winding,  $L_s$  is the secondary winding, C is the output capacitor, and R is the load.

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Fig. 1. The conventional flyback converter scheme [10].

The operation of the flyback converter consists of two stages according to the switch states. When the switch is on state, the diode is off state depending on the direction of the voltage which is reflected to the secondary winding of the transformer. The magnetizing inductance is equal to the primary inductance. The input voltage  $V_{dc}$  is applied to the magnetizing inductance, and magnetizing current increases, linearly. In this interval, the input energy is transferred to the primary inductance and the load is fed from the output capacitor. When the switch is off state, the diode is turned on, and reflected output voltage is applied to the magnetizing inductance. So, the magnetizing current decreases, linearly, and the magnetizing energy is transferred to the output through the secondary winding [10–16].

Since, the main current is equal to the magnetizing current, the flyback transformer is designed with the air gap. However, the air gap results in leakage inductance and additional voltage stresses. These disadvantages can be overcome using proper snubber cells. For this reason, flyback converters are preferred for low-power applications [10–12].

Flyback converters may operate in discontinuous current mode (DCM) or continuous current mode (CCM) according to the current of magnetizing inductance as shown in Fig. 2. In CCM operation, the magnetizing current does not decrease to zero during the switching period. So, the energy transfer is continuous. Therefore, it is preferred in high-power applications. In DCM operation, the magnetizing current falls to zero and remains at zero for a time during the switching period. The current stress of the switch and electromagnetic interference (EMI) is higher than CCM operation [13–15]. However, DCM operation provides higher efficiency than CCM operation in low-power applications due to no reverse recovery loss of the secondary diode and zero current switching of the MOSFET and secondary diode. Moreover, DCM operation provides advantages

#### **Main Points**

- Designed KNX power supply is a high frequency (100 kHz), high efficiency (minimum 85%) flyback converter-based.
- Output voltage has low ripple.
- Oscillations in the KNX power supply are suppressed by snubber cells.



**Fig. 2.** Typical flyback converter. (a) DCM operation. (b) CCM operation [10].

such as ease of control, small core, fast response, and soft switching in low-power converters.

#### **III. KNX POWER SUPPLY DESIGN**

Fig. 3 shows the circuit scheme of the flyback converter-based power supply which is designed for KNX standards. Here, EMI filter, bridge diode, and  $C_i$  filter capacitor are used at the input and choke is used at the output. Also, the leakage inductance of the transformer and the parasitic capacitor of the diode are taken considered. Therefore, the RCD snubber is connected 'parallel' to the primary winding and the RC snubber is connected parallel to the diode, and the RC snubber is connected parallel to the MOSFET.  $V_{DS}$  voltage of the MOSFET increases up to 600 V and the maximum current flowing through the MOSFET while it is in on state is 1.4 A. Therefore, NCP11187 control IC is chosen. This IC integrates 800 V Super junction MOSFET [9].

In the control circuit of the proposed KNX power supply, conventional Pulse Width Modulation is used with output voltage and output current feedback. In KNX power supplies, the voltage range and current values specified in the standard should not be exceeded. Therefore, two compensators for fixed voltage and limited current are used for feedback purposes in the control circuit, as shown in Fig. 3. The oscillations of the feedback voltage cause instability in the power supply control IC. Moreover, these oscillations cause additional oscillations at the switching frequency. To prevent these oscillations, a compensation circuit is established with R1-C1 and R2-C2 components, as shown in Fig. 3 [9].

#### A. Input Capacitor Design

In flyback converters, the filter capacitor used after the bridge diode in the input part is designed to allow the input voltage to oscillate at a certain rate. In the literature, the value of this capacitor is chosen to be  $2-3 \mu$ F per W [12]. At the proposed KNX power supply, the output voltage is 30 V, the maximum current is 1.4 A, and the output power TEPES Vol 3., Issue. 2, 90-96, 2023 Solmaz Akar et al. Design and Implementation of a Power Supply for KNX Protocol



is 42 W. Therefore, the input filter capacitor is calculated as 100  $\mu$ F. The minimum DC input voltage value formula is given as follows:

$$V_{dc_min} = \sqrt{V_p^2 - 2P_{in}t\frac{1}{C_i}}$$
(1)

The minimum input voltage ( $V_{dc_min}$ ) is calculated using the formula and measured as 109.7 V. Simulation result is performed based on the selected capacitor value and the given formula is presented for 90  $V_{AC}$  in Fig. 4.

According to the 2.7.7 Testing of Power Supply Unit's (PSU) Hold-Up Time test of the KNX Standard "Basic and System Components/Devices - Minimum Requirements," if the mains voltage is interrupted for less than 100 ms, the output voltage should not decrease more than 5%. Thus, in the Hold Up Time test in the proposed power supply, the time elapsed from the moment when the mains voltage is interrupted to the point where the output voltage drops below 95% is measured while the system is operating. The minimum operating voltage of the system



is determined according to KNX requirements by measuring this interval under different main voltages. According to this requirement, the minimum supply voltage of the KNX Power Supply is measured to be 155  $V_{AC}$  [9].

#### **B.** Transformer Design

The transformer design of the converter is performed considering the worst conditions (minimum input voltage and maximum duty cycle). Therefore, the formula for the magnetizing inductance is given as follows [12].

$$L_{M} = \frac{\left(V_{DC\_min}D_{max}\right)^{2}}{2P_{in}f_{e}}$$
(2)

Herein,  $P_{\rm in}$  is the input power,  $f_{\rm s}$  is the switching frequency. In DCM operations, the required maximum duty cycle  $D_{\rm max}$  is chosen 0.5 for the circuit to operate at the worst conditions. Thus, in the proposed design, the magnetizing inductance is calculated as 599  $\mu$ H for the input power is 25.1 W,  $V_{\rm DC}$  min 109.7 V,  $f_{\rm s}$  100 kHz, and  $D_{\rm max}$  0.5 [9].

In flyback converters, the current flowing through the switch during turn-on is equal to the magnetizing current. This current depends on the input voltage, and it increases linearly [10–13].

$$i_{LM} = i_{ds} = \frac{V_{dc}}{L_m} t$$
(3)

The maximum primary current of the converter is calculated as 0.93 A by considering the worst conditions. In this case, the required number of turns to avoid the saturation of the transformer is calculated depending on the following formula [9].

$$N_{p} = L_{M} \frac{i_{DS\_max}}{B_{sat}A_{e}}$$
(4)



Here,  $B_{sat}$  is the saturation value of magnetic flux density for ferrite cores, and it is defined as 0.3 Tesla.  $A_e$  is the effective area of the core. In this paper, EF25 type core is selected with  $A_e$  is 52.5 mm<sup>2</sup>. Thus, the number of primary turns is calculated as 53 according to (4) [9].

The turns ratio (n) of the transformer is calculated by using the value of the voltage reflected from the secondary to the primary and the voltage stress of the switch. When n is selected high, the voltage stress value of the switch increases, and when it is selected low, the circuit does not operate properly. For this purpose, n is calculated according to the following formula [12, 16].

$$n = \frac{V_r}{V_o + V_{diode}}$$
(5)

Here,  $V_r$  is the reflected voltage,  $V_o$  is the output voltage, and  $V_{diode}$  is the forward voltage of the diode. In these calculations, the forward voltage of the diode is taken as 0.5V. Thus, the value of n is calculated as 3.

#### C. The Calculation of the Output Capacitor

In the application notes of the switch-mode power supply control IC (NCP11187), it is recommended to determine the output capacitor as 100  $\mu$ F per 100 mA. Since the current of the designed power supply is nominal 0.711 A, the capacitance value is determined as a minimum of 720  $\mu$ F. At the same time, according to the KNX requirements, the output voltage ripple value should be less than 100 mV. Therefore, the Equivalent Series Resistance (ESR) value of the selected capacitance should be less than 15 m $\Omega$ .

#### **IV. CHOKE COIL DESIGN**

In the KNX system, the most common communication for KNX installations is provided by twisted pair data cable. The twisted pair data bus cable provides both data and power to all devices. The data transfer rate is 9600 bits/s (104  $\mu$ s). The logic zero consists of two parts: an active pulse and an equalization pulse as shown in Fig. 5(a). The voltage falls for a short time and then increases again after a maximum of 104  $\mu$ s to equalize the original voltage. This is due to the inductor effect of the choke. During the equalization part of the choke coil, it restores the energy used in the active part of the 0-bit. In the case of logic one, the DC voltage level is 30 V [7].

The circuit which is shown in Fig. 5(b) is used in the choke coil design according to the Clause 5 TP1 Choke section of the KNX Standard "Basic and System Components/Devices - Minimum Requirements." The choke shall be designed as electrically symmetrical to improve noise immunity and decrease radiation on the bus [5].

#### **V. EXPERIMENTAL RESULTS**

The experimental circuit parameters determined by considering the design criteria of the proposed converter are given in Table I.

	TABLE I.	
	CIRCUIT PARAMETERS	
Parameter	Description	Value
<i>C</i> <sub><i>i</i></sub>	Input filter capacitor	100 µF
C <sub>o</sub>	Output filter capacitor	810 μF
L <sub>o</sub>	Output filter inductance	1 μH
L <sub>p</sub>	Primary inductance	560 μH
L <sub>s</sub>	Secondary inductance	62 μH
L <sub>k</sub>	Leakage inductance	4.3 μΗ
NCP11187	Control IC	_
MUR340	Diode	300 V-3A







Fig. 7. The voltage and the current waveforms of the MOSFET.

Fig. 6 shows the voltage stresses of the MOSFET for 220 V input voltage. Here in Fig. 6(a), the peak voltages due to leakage inductance in the switch and the oscillations due to the parasitic capacitor of the diode have high values, causing additional losses and noise. In Fig. 6(b), the RCD snubber cell connected to the primary and the RC snubber cell connected to the diode are added to the circuit. It is clear from this figure that oscillations and peak voltages are suppressed successfully.

Fig. 7 shows the voltage and current waveforms in the MOSFET when the input voltage is 220  $V_{AC}$  and the output current is 640 mA. Herein, it is seen that the current increase linearly from zero and provides Zero Current Switching (ZCS).

The output voltage and feedback voltage waveforms are shown in Fig. 8 (a). Here, resistance and capacitance are not used for compensation in the feedback circuit. Therefore, ripples in the feedback







voltage are clearly visible. In Fig. 8 (b), output voltage and feedback voltage waveforms are shown when a compensation circuit is added to the feedback circuit. It is observed that the ripples in the feedback voltage are suppressed with the added compensation circuit. In Fig. 8, it is seen that the output voltage reaches 30 V in 25 ms. At the same time, there are no overshoot or ripples in the output voltage.

In Fig. 9, the ripples in the output voltage are given taking into account additional compensation components and snubber cells. It is clear that the ripple is around 20 mV, while the output current is 640 mA.

The signal shape during data transferring in KNX is shown in Fig. 10. It can be seen that this signal shape is provided in accordance with KNX standards.

# **VI. CONCLUSION**

KNX Power supplies have 160 mA, 320 mA, 640 mA, 960 mA, and 1280 mA nominal output current options, taking into account voltage and current limitations according to KNX standards. This makes



KNX power supply special among the others. Moreover, the twisted pair data bus cable provides both data and power to all devices.

The choke is used for data transfer at KNX systems. The special circuit structure at the output line, during the equalization part of the choke, restores the energy used in the active part of the 0-bit, and the efficiency is increased.

Flyback converters are widely used in low-power applications due to their isolation, ease of control, and simple structure. It also provides DCM for soft switching in low-power applications and increases efficiency in converters.

In this paper, a flyback-based power supply in accordance with KNX standards, operating with DCM has been designed and implemented for 155–265  $V_{\rm AC}$  input and 30V 640 mA output values. As a result of the application, output voltage ripple limitations, output current limitations, and data transfer are achieved successfully. Moreover, voltage peaks and oscillations due to leakage inductance are minimized by snubber cells.

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# REVIEW

# Dynamic Modeling Guidelines for Wind Power Plants: Australian Test Case

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#### ABSTRACT

As wind power generation increases, power system operators are challenged by the detailed modeling and simulation of wind power plants to realize the behavior and to maintain the stability of their power systems. In order to investigate the performance of the wind power plants, dynamic root mean square (RMS, 50 Hz phasor dynamics) and electromagnetic transient (EMT) models are very crucial with standards and guidelines. These dynamic models have been developed in the last two decades by the wind turbine manufacturers and plant and power system tool developers. In accordance with this progress, Australian Energy Market Operator (AEMO) has published a dynamic modeling acceptance test (DMAT) to assess the accuracy, consistency, and robustness of RMS and EMT models used for power system analysis. In this paper, DMAT is summarized to introduce how AEMO guides the modeling aspects of wind power plants in their power system. Additional inputs have been discussed to improve the modeling perspective for the future guidelines.

Index Terms—Dynamic modeling, grid codes, wind power plants, wind turbines

#### I. INTRODUCTION

Renewable energy is a type of alternative energy that is a candidate to solve problems of traditional carbon-based electricity generation regarding sustainability and ecology. Due to problems such as global warming, the reliability of energy supply, the accessibility of fossil resources, the limited diversity of energy sources, and fluctuations in energy prices, almost every country in the world has started to question the method of electrical energy production and accelerated the investments in renewable energy methods such as wind and solar energy (Fig. 1). First of all, there should be a good financial potential for the development of the electrical grid and the sustainability of the renewable energy investments. In addition, the power systems planned to be implemented must be suitable for the technical infrastructure in the region where it will be installed. The grid integration criteria to be provided for the technical infrastructure are specified in the grid code requirements of each country [1-3]. Grid codes vary from country to country, and they are technical documents for the electricity generation and consumption facilities created specifically for that country and global standards.

For island countries that do not have electrical connections to neighbor electrical grids, grid codes are more demanding compared

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to other grid code requirements. Due to their geographical conditions, the island power systems, which need to be self-sufficient in terms of energy balance, have been required to meet more stringent technical requirements for stable and reliable operation. Japan, UK, and Australia are examples of these island power systems. Although Australia has a geographically very large area among these island countries, human settlement and most of the energy needs of the country are on the west and south coasts (Fig. 2). Furthermore, the established and planned wind power plants with high wind potential are in the western and southern parts of the country [4]. Since the wind power plant to be established in these areas will have to transmit the electricity along long lines and there is a high probability of faults in these transmission lines as a result of various natural events. it is desired that the wind power plant to be established will meet challenging conditions regarding the fault management, voltage, and frequency control.

As a result of the advancement of the computing power of computers, power system analysis simulation tools results validated the real time power system behaviour, hence it is desired to report the simulation results of wind power plants as the pre-installation evaluation criteria at the application phase. In order to ensure that these criteria

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Fig. 1. Distribution of renewable energy investments between 2015 and 2021 according to regions and energy types [5].

are met, it is requested to certify the dynamic model acceptance test (DMAT) [6] results to the Australian Energy Market Operator (AEMO) during a project application phase. Dynamic model acceptance tests must be successfully carried out by all technology providers (conventional generators, wind turbines, and solar plants) and companies. Dynamic model acceptance tests, which will be explained in detail later, aim to show the performance of the dynamic models of the power plants during fault and normal operating conditions. The DMATs mentioned here will be performed for electromagnetic transient (EMT) dynamics and root mean square (RMS, 50 Hz phasor dynamics) models using the Power Systems Computer Aided Design (PSCAD) and Power System Simulation for Engineers (PSS/E) software. Some tests in DMAT require only EMT analysis, while some tests require analysis for both EMT and RMS models. In addition, RMS and EMT test results should be benchmarked in the DMAT report with the results.

In this paper, DMATs required by AEMO for the connection of power plants are explained in detail, and the tests during faults and normal operating conditions are summarized, respectively, in the second section. In the third section, the DMAT procedure is discussed regarding the parameters and information that are given in the DMAT and possible improvements in future DMAT releases for clarity. In the conclusion section, the difficulties in the Australia electricity grid, caused by Australian island country conditions, are briefly summarized. Furthermore, some of the Australian grid issues that can be used in Turkey, are summarized in the conclusion section.

# **Main Points**

- This study revealed the effects of weak grids on the performance of power plants.
- It analyzes the importance of Dynamic modelling of power plants at grid integration.
- It analyzes the impact of the steady-state operation and fault conditions at wind farm level in EMT and RMS models.
- It discusses for future requirements and studies in Turkish Power System.

#### A. Grid Codes and Dynamic Model Acceptance Tests

When a wind power plant is connected to the transmission system, some of the technical capacities of the wind turbine have to comply to specific requirements which are published by countries' transmission system operators (TSOs). These technical requirements usually named as grid codes. Grid codes have an important role in sustaining the stability and reliability of transmission systems. The advantages of the conventional power plants are the inertia of the generator, voltage backup to the grid during faults, and power synchronizing. Because of these advantages, power plants having synchronous generators help to create sustainable and reliable electrical power grids. However, inverter-based resources do not have not the same capabilities. Grid codes define the operation ranges of frequency and voltage. Active and reactive power controls are checked with grid codes. With fault ride through and reactive current injection requirements, grid codes define adequate and stable performance for wind power plants during grid disturbances.

Furthermore, wind power plant operation must be stable and predictable during both grid disturbances and normal operating



Fig. 2. Map of Australia power transmission lines [7].

conditions without any problems. There are frequency and voltage operating ranges that wind power plants should operate without changing their active and reactive power outputs. In addition to these ranges, there are limited and sudden disconnection operation ranges to protect both wind power plants and the power systems [6]. Since reactive power and voltage dynamics are closely correlated, through voltage control of the wind power plant, reactive power capability can be realized and can support the power system.

While grid codes differ from country to country and TSO to TSO, countries are updating their grid codes and additional technical requirements. One of the examples for this country is Australia. The Australian electricity grid, one of the island electricity grids that is not interconnected to operate, is undergoing a transformation because of the increased connectivity of renewable energy sources and energy storage systems. Compared to conventional power grids that have mostly synchronous generators, wind, and solar power plants with power electronics (converter and inverter based) interfaces react differently to failures and changes in the electricity grid [3]. Considering these different reactions, there are different electricity grid regulations for wind and solar power plants. The experience gained after failure during the operation of the wind farms in operation in Australia requires that these network regulations be updated over time. During these updates, AEMO requires both EMT and RMS dynamic models from all power plants to model the entire electrical power system and to predict future problems. When requesting these models, it is necessary to perform the tests in DMAT before the power plants' grid connection. The aim of the challenging conditions required in the simulation is to observe the performance of power plants in the weak grid condition that may be encountered in the island power systems. The definition of a weak grid is often understood by looking at the low short circuit rate (SCR) value. Short circuit rate is the ratio of the short circuit power of the power plant at the connection point to the nominal power of the power plant [(1) and (2)].

$$SCR = \frac{Scc(MVA)}{Pn(MW)}$$
(1)

$$SCR = \frac{Sb(MVA) / Xpu}{Pn(MW)}$$
(2)

$$S_b$$
 and  $P_n$  are equal  $X_{pu} = \frac{1}{SCR}$ 

Although the common calculation method of SCR is mentioned above, there are three other SCR calculation methods. Equivalent short circuit ratio (ESCR) is preferable when the wind plant to be evaluated does not share connection point with other wind plants (3).

Composite short circuit ratio (CSCR) can be preferable when the wind power plant shares medium voltage (MV) connection. Specifically, in this case, both power plants are directly summed, and evaluation is done as they are single elements (4).

Weighted short circuit ratio (WSCR) can be employed for checking the contribution of each plant to the power system (5).

$$ESCR = \frac{Scc(MVA)}{Pn(MW) + \sum_{j} MIIF_{j,j}Pn_{j}},$$
(3)

where  $MIIF_{j,i}$  is a participation factor that  $MIIF_{j,i} = \frac{\Delta Vi}{\Delta Vj}$ 

V

$$CSCR = \frac{Scc_i(MVA)}{\sum_i Pn_i(MW)}$$
(4)

$$VCR = \frac{\sum_{i}^{N} Scc_{i} (MVA) Pn_{i}}{(\sum_{i}^{N} Pn_{i})^{2}}$$
(5)

Table I details all methods and provides a comparison of all of them [8].

In general, electrical systems with SCR 3 or below are considered as weak grids [9]. Extra tests have been added within the DMAT to ensure that wind power plants in particular are likely to obtain stability issues in weak grids and to see the performance of these power plants planned to be built in Australia. While SCR values of 14 and 10 are used for performance as a normal network condition, it is desirable to analyze models for SCR value 3 and below for the performance of the same tests.

For preparation DMAT results, the model of the power plants must be modeled in the computer environment (PSCAD and PSS/E software) with the electrical model of wind turbine grid connection given in Fig. 3 and perform many different scenarios completely and stably. In the DMAT, it is requested to analyze many different scenarios such as FRT (fault ride through) performance, active power, reactive power, the attitude of the control system in the model against changes in voltage reference, observation of the effect of frequency

TABLE I.           COMPARISON OF DIFFERENT SCR CALCULATION METHODS				
Index	Simplicity	Determine Maximum Capacity of a Specific Bus	Consider Other Plants Adjacent	Considers STATCOM or SVC
SCR	++	++	Х	х
ESCR	х	Х	++	++
CSCR	+	+	+	х
WSCR <sub>MW</sub>	+	Х	++	++
WSCR <sub>MVA</sub>	+	Х	++	Х

++, high; +, medium; X, low.

CSCR, composite short circuit ratio; ESCR, equivalent short circuit ratio; SCR, short circuit ratio; WSCR, weighted short circuit ratio.





changes in the model, how the model will perform in the weak network conditions. In the DMAT setup (Fig. 3), the signals that should be recorded and analyzed as the outputs of the simulation are indicated in Table II.

Fault ride through is a test scenario in which wind power plants must sustain the fault conditions and support the power system even for very low voltage levels. For checking these scenarios, after the grid disturbance occurs and the voltage dip happened at Point of Common Coupling (PCC), wind turbine would stay connected and after the fault cleared, it must return to its initial operating point condition. After having the simulation results of the FRT test cases, the performance of the model should be evaluated considering the grid connection requirements and the performance.

Dynamic modeling acceptance tests such as active power reference, voltage reference, and reactive power reference tests are purposed to check wind power plant controller response together with wind turbine model against reference changes. Moreover, some of the power reference tests are requested at a very low SCR grid (SCR = 1). For changing the input power of the wind turbine with changing

TABLE II.           IMPORTANT SIMULATION OUTPUT SIGNALS			
Active Power	Active Power Reference	Reactive Power	Reactive Power Reference
Inside turbine voltage	Outside turbine voltage	Grid frequency	Active power current
Active power current reference	Reactive power current	Reactive power current reference	Total current
Negative sequence current	Negative sequence voltage	Negative sequence current reference	Terminal voltage
Terminal voltage phase angle	Rotor speed	One-phase terminal RMS voltage	
RMS, root mean square.			

wind speed, the dynamics of the model for following the active power reference is tested in DMAT.

Additionally, the frequency tests in DMATs are proposed over an extended range of the nominal operating points. Wind power plant response against temporary frequency deviations under and over the nominal frequency value has been captured applying these frequency tests. Dynamic modeling acceptance tests include additional and unique tests due to Australia's unique geographic conditions. With these additional test cases, wind power plant's low SCR capability is tested and analyzed for its sustainable performance.

#### B. Three-Phase Balanced Fault Ride Through Cases

In this DMAT scenario, it is aimed to assess the response of the wind power plant model during and after a three-phase fault of 0.43 and 0.5 s. The active power reference of the wind power plant is 1 pu and 0.05 pu, and the reactive power reference value is 0, 0.3, and -0.3 pu. The SCR values are 3-10, and the *X*/*R* (ratio of the reactance value to the resistance value at the connection point) values are specified as 3, 10, and 14 to form the strong and weak operating conditions of the power system. In total, 36 simulations are required using different combinations of parameters considering the SCR, *X*/*R*, active power, reactive power reference, voltage reference, fault impedance, and fault duration.

#### C. Unbalanced Fault Cases

For unbalanced fault situations (phase-to-phase, two phase-toground, and single phase-to-ground), it is aimed to observe the behavior of the wind power plant model considering various active and reactive power references. In general, the fault durations are 0.43 s, but for some of the specific cases, the line-to-line fault duration is 2 s. As it can be understood from this long fault duration, the model should be tested in extreme cases. In these cases, the performance of the wind power plant model should again be reported with different combinations of active power reference, reactive power reference, X/R and SCR values, and fault impedance parameters.

#### D. Multiple Fault Ride Through Test Cases

Due to the extreme weather events (e.g., lightning strikes) in Australia, there had been a large number of consecutive faults on the transmission lines. These multiple faults caused disconnection of wind power plants and endanger the operation of the Australian

TABLE III.           MFRT RANDOM EVENT SELECTION FOR EMTP MODEL TEST		
Randomly Created		
Fault type	$6 \times$ 1 PHG, 7 $\times$ 2 PHG, 2 $\times$ 3 PHG	
Fault duration (ms)	8× 120 ms, 6× 220 ms, 1× 430 ms	
Time between recurring events (s)	0.01, 0.01, 0.2, 0.2, 0.5, 0.5, 0.75, 1, 1.5, 2, 2, 3, 5, 7, 10	
Fault impedance	$7 \times Z_f = 0, 5 \times Z_f = 3 \times Z_s, 3 \times Z_f = 2 \times Z_s$	
MFRT, multiple fault ride through.		

power system. Therefore, the wind power plants have been required to sustain the multiple fault ride through (MFRT) operation. The variable number of consecutive faults, which occur at different times, is selected from the values specified in Table III. The main aim is to show the sustainable operation of the wind power plant model together with the control and protection systems.

#### E. Temporary Overvoltage Test Cases

The performance of the wind power plant model, which is operating at 1 pu, is tested against the overvoltage situations for the level of 1.15 pu voltage of 0.9 s and 1.2 pu voltage for 0.1 s. These overvoltage test scenarios are set up by activating the capacitor group after the PCC to the grid side. The reactive power reference was determined as 0, 0.3, and -0.3 pu. The SCR values of the over-voltage testcases are 10, 3 and the actual SCR value of the region where the project is going to be installed, the *X/R* value is 14, 3 and the actual *X/R* value of the project site.

# F. Voltage/Reactive Power/Power Factor Reference Change Test Cases

During the 45-s simulation, the wind power plant model reacts to the 5% voltage rise and fall (Figs. 4 and 5) that will occur in the grid voltage and wind power plant's voltage reference change. In addition to these tests, the performance of the model is considered after the increase and decrease of 0.3 pu in the reactive power and power factor reference. In each reference scenario, SCR values set to 10, 3 and project-specific SCR value, X/R values set to 14, 3 and projectspecific X/R value.







#### G. Active Power Reference Change Test Cases

In these test cases where the active power starts from 1 pu, the capacity of the active power to follow the reference is changed by gradually setting the active power reference to 0.05 and 0.5 pu (Fig. 6). Reactive power reference is kept constant at 0 and 1 pu for this test case. Three test cases are proposed, with SCR and X/R combinations being 10 and 14 and 3 and 14, respectively, including also the actual PCC values.

#### H. Grid Frequency Change Test Cases

Grid frequency change tests are proposed according to a 2 Hz increase and to a 3 Hz decrease in network frequency with different rates. Furthermore, test cases are created by setting the potential power that the wind power plant can produce as 5%, 50%, and 100% and setting the active power reference differently. For 2 Hz increase scenarios, the active power reference is set to 0.05 and 0.5 pu, and for a frequency drop of 3 Hz, the active power reference is set to 0.05, 0.5, and 1 pu. The aim of this test case scenario is observing whether the results of frequency changes are that the system follows the active power reference (Figs 7 and 8).

#### I. Grid Voltage Oscillation and Angle Change Test Cases

These are the cases created to test the response of the wind power plant model to 10-s oscillations in the grid voltage with different











Fig. 8. Grid frequency test-underfrequency.



**Fig. 9.** Oscillatory rejection tests (example of 1–10 Hz in steps of 1 Hz per modulation).

oscillation frequencies. For 10 s, nine different cases from 0.1 Hz to 0.9 Hz and additionally 45 different oscillations from 1 Hz to 45 Hz are listed (e.g., Fig. 9).

#### J. Wind Speed Change Test Scenarios

When the active power reference is set to 0.5 and 1 pu, a 20% increase and decrease in input source (wind speed variations) is tested to see if the model can follow the active power reference. These tests are important for the control performance when the available power is different from the active power reference value during the simulation duration. For normal operating conditions, active power reference will follow the available power coming from the actual wind speed value. However, if there is a need for active power curtailment according to market conditions, a frequency control requirement, or a contingency as an immediate action, the control performance is very important.

#### K. Test Cases for the Low Short Circuit Rate at the PCC

These are cases where the X/R value is set to 3 and 10 when the SCR value is selected as 1, and the active power reference is proposed to start from 0.05 pu and gradually increase to 0.2, 0.4, 0.6. 0.8, and 1 pu, respectively. These cases are special tests for wind power plants' connection to the South Australia region. This population density of South Australia is not as much as eastern part of the country. Thus, most of the generated electrical power should be transmitted with longer transmission lines. Long transmission lines create weak grid conditions for the wind power plants in South Australia. Together with the extreme events and faults, wind power plants must obtain the expected minimum SCR value conditions in DMAT. One of the purposes of these cases is to observe the maximum power that the wind power plant can sustain a stable operation with the given low SCR value. In addition to the test cases which have same SCR value during the simulation, additional test cases have been required to understand how the wind farm will perform when the SCR value changes after the fault (e.g., reducing it from 3 to 1 as an example of N-2 tripping a line after a fault). In these additional cases, it is aimed to observe that, at severe fault conditions, wind power plant's protection and control systems activated and deactivated properly.

#### **II. DISCUSSION**

Australian Energy Market Operator prepared the DMAT guidelines to assess the accuracy, consistency, and robustness of dynamic models with a wide scope according to the specific characteristics of both the weak grid, the normal grid, and the grid where the turbine will be installed. However, the operating conditions of the power plants can be defined in more detail. For example, while the SCR values and X/R values of the tests are defined precisely, the parameters such as fault type, fault duration, fault impedance, active power reference, reactive power/voltage/power factor reference, and the operating conditions on the electrical network side can be defined also in terms of the grid voltage magnitude. Another important point is to define or give a range for the power plant transformer's tap changer settings depending on the load flow. At the same reactive power reference, there can be different cases when the combination of the tap change, the grid voltage, and the PCC voltage magnitude. They all affect the load flow.

Since wind power plants consist of tens of turbines, instead of modeling the performance of the whole power plant individually with each turbine, it is aimed to model it as a single aggregated wind turbine model. However, the methodology in DMAT is not specified whether it will be on the low-voltage side of the wind turbine or on the medium-voltage side at the collector grid of the power plant. When the saturation curve is modeled in both unit and power plant transformers, the aggregated and detailed models might have different results especially in EMT simulations.

#### **III. CONCLUSION**

The transition from conventional to renewable energy generation has been progressing to reach sustainable and clean power system goals. Among the renewable energy, wind energy is the prominent way with the efficiency and the wind resource distribution. The integration of the power plants into power systems is important for a stable and reliable operation. The grid codes and requirements are very crucial and should be progressive. Although the grid codes that vary from country to country are shaped according to the specific conditions of the countries, the technical conditions and the desired criteria that are not available in other countries provide new ideas in creating and strengthening the network control and operations. Since the simulation models contain sufficient information about the performance and capability of the power plants, they are required in the pre-evaluation of the power plant application in Australia.

The DMATs are required by AEMO to guarantee the robustness and functionality of the power plant models before the grid connection. DMAT can be accepted as ambitious sets of tests, since the details of test cases, and their compliance requirements are not the same for the other power systems in the world. Although it does not have an island network operation like Australia, in Turkey, the DMATs can give ideas for the future progress of the renewable energy and provide benefits by performing simulations of possible faults and events with the help of RMS and EMT simulation environments. Because of the simulation results that are close to the real performance of the power plants for the normal and transient conditions, the measures to be taken will be determined, and possible solutions will be produced in advance. In this way, time and cost savings will be realized.

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