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DESIGN AND IMPLEMENTATION OF SMART TRANSFORMER BASED CONTROL OF DISTRIBUTION GENERATION IN DC BUS

Gaurav Chauhan[1]*, Sakshi Bangia[2]
[1]Department of electrical Engineering, J.C. Bose University of Science and Technology, YMCA, Faridabad, Haryana, India
[2]Associate Professor, Department of electrical Engineering, J.C. Bose University of Science and Technology, YMCA, Faridabad, Haryana, India

Abstract: The variations caused by the distributed generation (DG) results in fast changes in the overall load composition and have a significant impact on the power response during voltage fluctuations. The Smart Transformer is a power electronic based distribution transformer accompanied with advanced control technologies that can analyze the dependence of load on voltage for improving the quality of power supplied to the transmission and distribution grids. The high control capability of the smart transformers makes it an ideal choice for optimizing the power flow management and control of the DG system. The deployment of smart transformers enables the control of voltage in the DC bus and thereby manages the system operation under fault occurrences. During faults, the smart transformer can swiftly reduce the voltage which is in phase and thereby ensures the safety of the DC bus and can operate with other phases to prevent interruption with faulty phases. However, the effects of harmonics in the DC voltage reduces the lifespan of the capacitors and increases the flow of high current in the system. These issues can be mitigated by increasing the maintenance of the smart transformer in order to prevent dynamic faults in the system. This paper presents a flexible control strategy for smart transformers based on DG in a DC bus. The performance of the proposed approach is evaluated in terms of load power, PV power, wind power, fuel cell power and power transfer between grid and the transformer.

Keywords: *Smart Transformer, Distributed Generation (DG), Renewable Energy Sources, DC DC converter, Load Power*

1. Introduction

The implementation of distributed generation (DG) is significantly increasing in the distribution grid incorporated with renewable energy sources (RES) such as photovoltaic (PV) systems, wind energy (Rezaei & Esmaeili, 2017) [1], and other energy generation sources such as fuel cell (FC) and battery as an energy storage system. However, excessive utilization of DG sources can introduce serious issues such as increased line losses, imbalanced load condition, reverse power flow, increased voltage harmonics etc (Lakshmi & Ganguly, 2018) [2]. Specifically, the distribution systems deployed for smaller loads such as residential areas experience increased power loss due to the high resistivity of distributive lines. The excess power loss increases the energy demand from the grid which in turn increases the energy cost and operating costs. Hence, it is essential to reduce the loss and energy demand from the grid in distribution networks (Lakshmi & Ganguly, 2019) [3]. In general, the energy demand mainly depends on the load and transmission losses. If the loads are considered as constant power loads then the reduction in the energy loss can be equated to the reduction in the energy demand of the distribution network, since it is practically not feasible to control the load power. Various techniques are available for minimizing the power loss in the distribution networks. Some of the prominent techniques are the utilization of capacitor banks (Dehghani et al., 2020) [4], allocation of DG sources (Abdel-mawgoud et al., 2017) [5], and network reconfiguration (Pegado et al., 2019) [6]. These techniques have proven their efficacy in reducing the energy loss. However, it is not easy to control the capacitor banks in continuous steps and this is one of the major drawbacks associated with it. To overcome this problem, it is suggested to implement power converters for reducing the energy loss. The power converters play an important role in enhancing the efficiency of the distribution networks. These converters are operated in two modes namely a grid forming model and a grid following mode (Ahmed et al., 2020) [7] based on the applied control technique. The power converters disguise themselves as AC current sources that provide active and reactive powers as per the requirement in the grid following mode. On the other hand, the power converters operate as AC voltage sources to maintain the frequency and terminal voltage based on the requirements in the grid forming mode (Rosso et al., 2021) [8]. In traditional AC grid systems, the reactive power from the DG systems can be controlled by operating them in the grid following mode. By effectively controlling the reactive power from DG systems, the voltage can be controlled. As mentioned in (Sarfi&Livani, 2020) [9], the reactive power can be controlled using photovoltaic (PV) inverters to minimize the power loss and improve the voltage profile. Using PV inverters, the active power obtained from DG systems can be maintained at a fixed reference point of the maximum power point (MPP) power or the active power can be reduced. Hence, the DG converters are less utilized when the DG sources cannot supply sufficient power to the system. The DG sources are mainly the renewable energy sources (RES) such as solar energy or wind power. In such cases, it is necessary to deploy an operating DC system with the AC system or a hybrid system that combines both AC and DC systems. This improves the reliability and performance of the system and maintains the stability under uncertain conditions (Liang et al., 2019) [10] (Yoo et al., 2019) [11]. However, there are certain complexities associated with the utilization of the distributed generation sources such as solar and wind energy in hybrid AC/DC systems, which are mainly related to the power quality, poor management of power flow and reverse power flow in the system (Liang, 2016) [12]. These issues can be resolved by implementing a smart transformer, which is one of the popular solutions available for solving the power related problems in the distribution networks (Kumar et al., 2017) [13] (Gao et al., 2017) [14]. A smart transformer is a solid state transformer designed using power electronic converters with robust control functionalities and communication abilities. Different control techniques and architecture of a smart transformer is discussed in (Zhu et al., 2020) [15]. These techniques aim to improve the performance of the grid system. The smart transformer has attributes and functionalities similar to that of a traditional power transformer such as change of voltage level, isolation, and other properties such as load compensation, voltage and power control, and simultaneous frequency support (Liserre et al., 2016) [16] (Hrishikesan et al., 2020) [17]. The presence of DC links in the smart transformer model minimizes the number of converters required for connecting DC sources in the DG system and reduces the operational cost of (Giacomuzzi et al., 2020) [18]. In addition, smart transformers also enable the formation of AC/DC hybrid microgrids (Gupta et al., 2017) [19]. Considering the advantages, this research implements a smart transformer based control for DGs in a DC bus.

The prominent contributions of this paper can be summarized as follows:

- A Smart Transformer based control approach is implemented in this paper for distribution generation in the DC bus.
- A Permanent Magnet Synchronous Generator (PMSG) is used as a wind generator to generate the required electrical power and feed it to the grid.
- An ANFIS based Maximum Power Point Tracking (MPPT) controller is used for extracting maximum power from the PV system.
- A Boost converter is used to maximize the power supplied to the DC grid and a Bidirectional converter is incorporated with the system for charging and discharging.

The paper is further structured as follows: Section 2 discusses existing literary works related to the implementation of smart transformers for DG units. Section 3 describes the proposed research methodology which includes the implementation of the proposed smart transformer based control approach for DG system.. Section 4 discusses the experimental results and discussions based on the simulation analysis. Lastly, the conclusion of the proposed approach is discussed in Section 5.

2. Related Works

Several research works have emphasized the implementation of smart transformers for achieving better power control in DG systems (Zou et al., 2017) [20] (Gabbar & Sayed et al., 2016) [21] (Costa et al., 2017) [22] (Zou et al., 2016) [23]. The authors in (De carne et al., 2018) [24] implemented smart transformers for controlling the load by identifying the sensitivities. Two main actions are performed for achieving effective load control wherein the first action is to control the overloading of the smart transformer by controlling the voltage. The second action uses a soft load reduction technique which reduces the load consumption by avoiding the load disconnection. The controlling action depends on the accurate estimation of load dependence on the voltage and in this case smart transformers can provide real-time load measurement. The overall impact of the DG on the load sensitivity can be determined using the control hardware and a digital simulator. (Hrishikesan & Kumar, 2020) [25] presented a smart transformer based MVDC system connected with a meshed hybrid microgrid. The ability of smart transformers to construct the MVDC bus is investigated in this paper for establishing a MVDC distribution line by integrating the battery as an energy storage system (ESS). The reconfiguration of the MVDC system creates multiple paths for controlling the flow of active power in the hybrid microgrid system. In addition, the performance of the system is evaluated during voltage sag condition and the flexibility of operation is analyzed through simulation analysis. (Chen et al., 2021) [26] studied the implementation of smart transformers for dynamic control of reactive power and to control the voltage and frequency in the grid system. The demand for supporting both frequency and load is controlled to reproduce inertia. A 250 kVA, 10 kV/ 400 V low voltage distribution network is considered for the experimental analysis and it is shown the variation in the demand is in the range of 6 - 10%. The simulation outcome can be used further to study the implementation of smart transformers for transmission systems, which validates the efficacy of these transformers to control the voltage and frequency. (Kumar et al., 2021) [27] discussed the impact of control for DG converters in smart transformer based meshed hybrid distribution networks. The optimal problem is formulated to determine a suitable power reference for the converters while controlling the load voltage and grid limit within the permissible limit by following the DG constraints. The efficacy of the smart transformers to reduce energy loss, improve voltage profile and minimize the operating cost is analyzed by comparing with other existing works.

3. Proposed Research Methodology

The preliminary objective of the proposed research is to implement a smart transformer based control for distribution generation in a DC bus. RESs such as a solar PV system, wind energy, fuel cell with the DC microgrid. The smart transformer is designed using a bidirectional DC DC converter.

3.1 Modeling of DG units*:*

The components of the distribution generation (DG) unit is modeled as follows:

3.1.1 Solar PV system

The solar PV system is modeled using 5 series strings and 10 parallel string modules to generate more power. The current and voltage characteristics of the PV systems can be determined from equation 1. These characteristics depend on the temperature and radiation (AbdelHady et al., 2017) [28]. The output current of the PV (I_{pv}) cell is obtained as a function of the output voltage of the PV cell is given as in equation 2.

$$I = I_{ph} - I_d[\exp(\frac{q(V+IR_S)}{kT_cA-1})] - \frac{(V+IR_S)}{R_{sh}} \qquad \text{.....(1)}$$

Where, I_{ph} = short circuit current due to photons (Sunlight), I_d = diode current, R = Load resistance, I = Load current, V=Voltage across load, R_s = Series resistance, R_{sh} = Shunt resistance, q = Electron charge (1.6 × 10 − 19 C) and k = Boltzman's constant (1.38 × 10 − 23 J / K).

The voltage-current characteristics of the PV cell are given as; (Fara&Craciunescu., 2017) [29].

$$I_{pv} - I_S\left[e^{\frac{(V+IR_S)}{nkT}]} - 1\right] - \frac{(V+IR_S)}{R_{sh}} \qquad \text{....(2)}$$

Where $I_s$is the saturation current of the diode.

The power generated by the PV cells is given as:

$$P_{pv} = \eta * V_{pv}I_{p} \qquad \text{….. (3)}$$

Where P_{pv} is the power generated by the PV cells, η is the efficiency of the converter, V_{pv} and I_{pv} are the voltage and current of the PV systems respectively.

In this research, a MPPT technique is employed for extracting maximum power from the PV modules under uniform and different temperature conditions. This research uses an Adaptive neuro-fuzzy inference system (ANFIS) based MPPT approach which provides better results compared to conventional MPPT techniques.Unlike conventional MPPT, the ANFIS-MPPT technique adjusts the duty cycle of the DC-DC converter for different environmental conditions and accurately maps the nonlinear input to the output. The ANFIS-MPPT approach ensures that a maximum power is extracted under fluctuating solar irradiance and improves the efficiency of the PV system. The ANFIS model integrates the effectiveness of the Artificial neural networks (ANN) and Fuzzy Inference System (FIS) and combines the attributes of both neural networks and fuzzy logic controllers. The ANFIS controller employs a set of fuzzy IF-THEN rules which can learn to approximate nonlinear functions. The block diagram of the FIS and the architecture of the ANFIS controller are illustrated in figures 3.1 and figure 3.2, respectively.

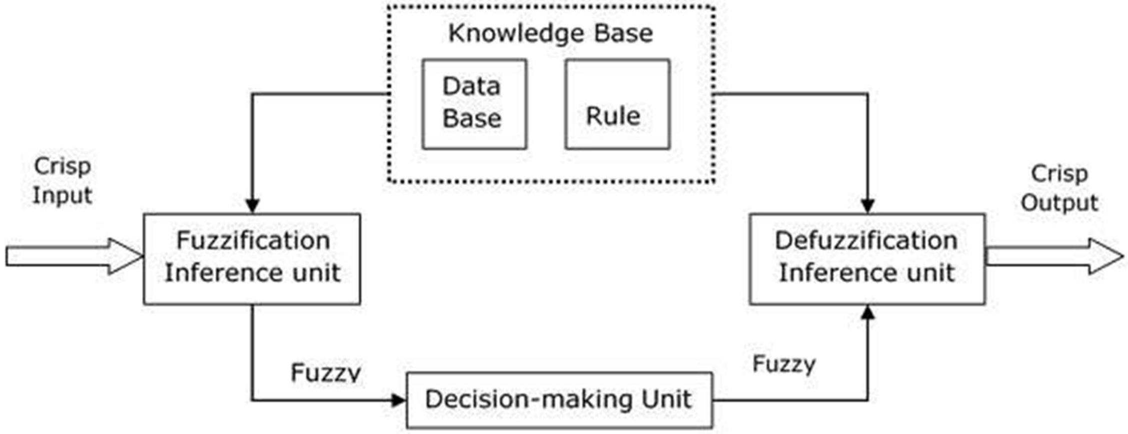

Figure 3.1 Block diagram of the fuzzy inference system

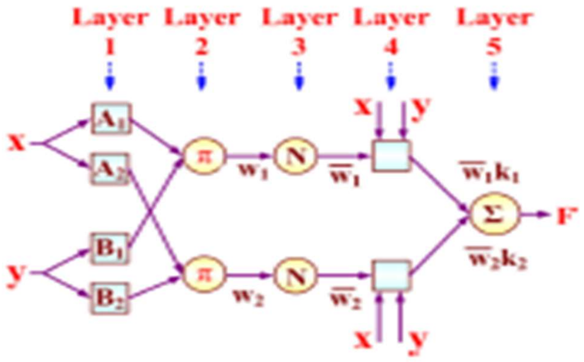

Figure 3.2 Architecture of ANFIS controller

As shown in figure 3.2, the ANFIS controller is composed of 5 layers. Fuzzification layer is the first layer which identifies the membership functions based on the input value. The second layer in the ANFIS is the rule layer which generates the firing strengths for the rules. The third layer normalizes the firing strength and the normalized values are given as input to the fourth layer along with the parameter set. The values returned by the fourth layer are defuzzified and are passed to the last layer i.e., the fifth layer for obtaining the final output. The inference rules in the controller are decided by tuning the input and output parameters using a back propagation technique and the controller is tested using a trial and error method to obtain an optimal value. The tuned parameters of the controller are transformed into fuzzy values based on the membership functions. In this work, the membership functions are obtained from the PV system. Three membership functions are selected based on the voltage-current output generated with the help of a controller.

3.1.2 Wind power generation:

A 4 kW wind energy generation system is incorporated with a permanent magnet synchronous generator (PMSG) which converts the kinetic energy (KE) of the wind into electrical energy.

The kinetic energy equation is given as

$$E = \frac{1}{2} mv^2 \qquad .....(4)$$

The KE is determined considering the fluctuations and availability of wind energy. Due to the variations, it is practically not possible to consider a constant value of velocity and density of the wind. In this research, considering the fact that the air density does not vary much with the variation in altitude and temperature, the power P of the wind energy is calculated as the rate of change of kinetic energy. The maximum power obtained by the wind turbine is restricted by the Betz law. Greater the wind speed, higher is the obtained energy. The input and output speed of the wind turbine is given as v_a and v_b respectively. The power generated by the wind turbine is given as:

$$P_{w(in)} = \frac{1}{2} A_s \rho_{air} V_a^3 \qquad .....(5)$$

$$P_{w(out)} = \frac{1}{2}A_s\rho(\frac{v_a+v_b}{2})(v_a^2 - v_b^2) \quad ....(6)$$

Where A_s is the area swept by the rotor, ρ_{air} is the mass density of the air and v_w is the wind voltage. $P_{w\,(in)}$ and $P_{w\,(out)}$ is the available input power and output power of the wind turbine respectively. For determining the output power of the wind turbine, the power is restricted by a rotor power coefficient (C_P). The maximum output power of the wind turbine based on C_P is given in equation 9 and 10.

C_P = (Power Extracted)/(Wind power) ....(7)

$P_w = (1/2) \times \rho \times C_P(\lambda, \beta) \times V^3 \times A$ ….(8)

Where β is the blade pitch angle λ is the tip speed ratio (TSR). The maximum rotor power efficiency is not greater than Betz limit value (0.593).

3.1.3 Fuel cell:

Fuel cells generate electrical energy using the chemical energy of hydrogen. The voltage characteristics of the fuel cell can be determined using Nernst equation as shown in equation 9.

$$V_{fc} = N\left[E_0 + \frac{RT}{2F}\left(ln\frac{P_{H2}P_{O2}^{0.5}}{P_{H2}}\right)\right] - r_{ohmic}I_{fc} \quad ….(9)$$

Where E_o is defined as the potential of the standard reversible cell, r_{ohmic} is defined as the internal resistance of the fuel cell, I_{fc} is the stack current of the fuel cell, N is the number of cells, R is universal gas constant, T is the temperature, F is Faraday's constant, P_{O2} is pressure of oxygen, P_{H2} is pressure of hydrogen and P_{H2O} is pressure of water. The effect of ohmic losses are ignored while calculating the output of the fuel cells. The reference current and the current through the fuel cell are determined as follows.

$I_{ref} = P_{ref} / V_{fc}$ **… (10)**

$I_{fc} = (I_{ref}) / (1+\tau_e^s)$ **....(11)**

Correspondingly, the power generated by the fuel cell is given as:

$P_{fc} = N\, V_{fc}I_{fc}$ **…(12)**

3.1.4 Battery management systems:

Battery management system is incorporated with the system. Here a bidirectional converter is implemented with the system so that whenever load is low or unavailable then the energy from the RES is transferred to the battery of the system via smart transformer. The battery can either charge or discharge too much power at one time. A Lithium ion battery is used which operates at a nominal voltage of 600 V and battery capacity of 50 Ah.

3.1.5 Smart Transformer

A smart transformer is designed using a non-isolated bidirectional DC-DC converter without an electrical barrier. This converter contains an inductor, two capacitors, and two switches that are of the same device type. The power of dc output is incorporated in the proposed smart transformer. Here the smart transformer is implemented in three stages namely; (i) Rectifier (ii) DC to DC converter, and (iii) Inverter., which are discussed as follows:

- ***Rectifier control***

The rectifier control in the smart transformer is shown in figure 3.3. This block is common to grid and DC converter and Renewable energy systems. Whenever the voltage is more at this terminal it transfers the power to the grid. When load required the power from Renewable energy transfers to the load.

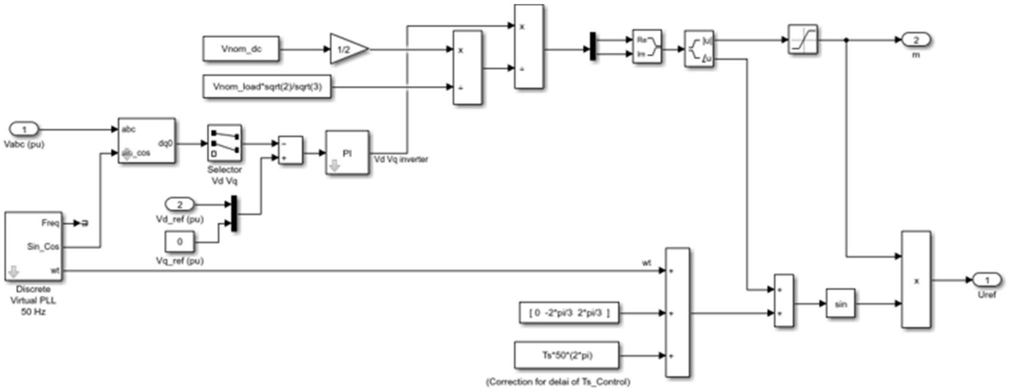

Figure 3.3 Rectifier control for smart transformer

- ***DC to DC converter***

This stage is one of the most difficult stages in the design of smart transformers, due to the complex requirements such as: high frequency isolation, high voltage and current in the MV and LV side respectively, high power requirement, and high efficiency. In order to satisfy all these requirements, this research employs a modular concept as shown in figure 3.4, wherein different modules share the total voltage and power among them.

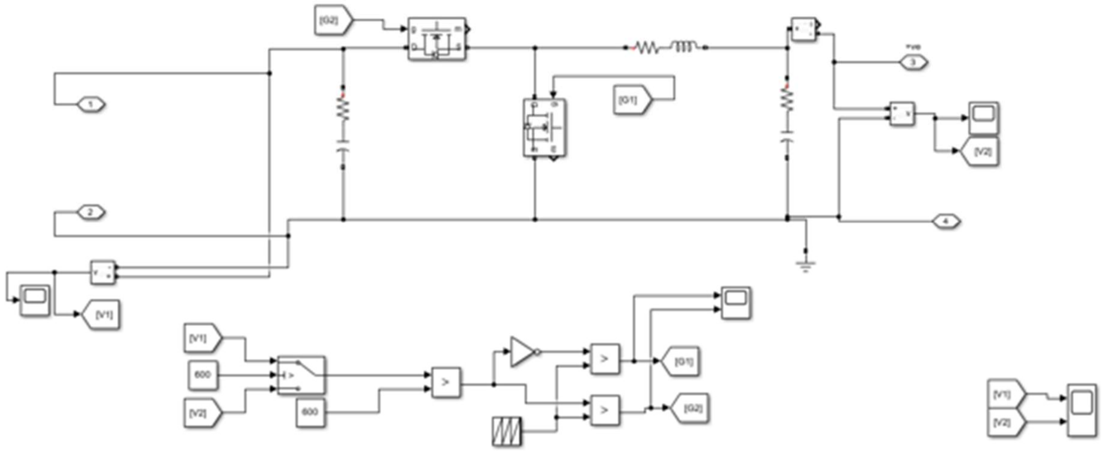

Figure 3.4 Smart transformer with DC DC converter

Let V_1 and V_2 be the levels of voltage and the bidirectional DC DC converter acts as a transformer and transfers the power accordingly. For instance, when the voltage V_1 is greater than V_2 then the converter transfers the power to V2 and vice versa.

- ***Inverter Controller***

The inverter controller for the smart transformer is shown in figure 3.5.

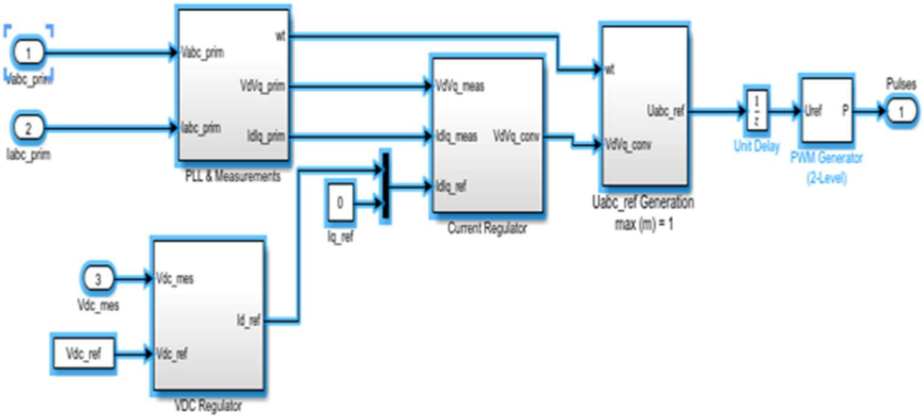

Figure 3.5 Inverter controller for smart transformer

Inverter is connected between load side, Battery storage system, and DC to DC converter. The output of the DC to DC converter is fed to the inverter side. The controller circuit generates pulses and control signals to the switch which can be used to regulate the power flow between the battery and the grid.

4. Results and Discussion

This section discusses the experimental evaluation of the proposed approach which is simulated using MATLAB/SIMULINK platform. The simulation is designed using a PV array of 20 kW configuration employed with an ANFIS based MPPT controller for extracting maximum power. The DC link is connected to a battery of 600V and 50 Ah. The simulation results of the PV power, wind power, fuel cell power, are illustrated in figures below.

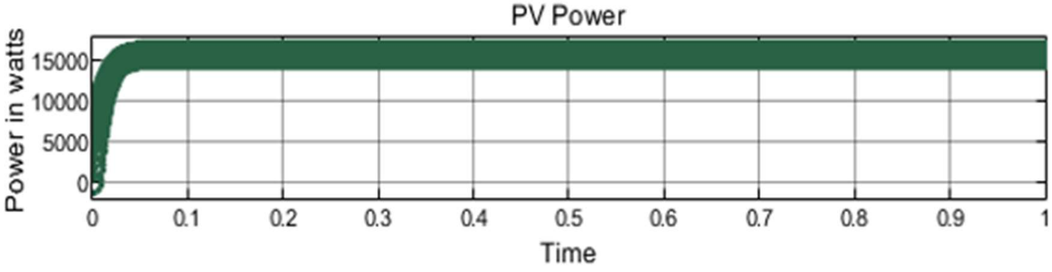

Figure 4.1 Output of the PV power

Solar temperature is constantly given as 25° C and maximum solar irradiation is obtained as 1000 W/m^2 and the maximum potential power of the PV system is 16KW. Here, the PV power generated is 15000 W in the whole time period with the ANFIS controller and applied 1000W/m^2 irradiation to the system.

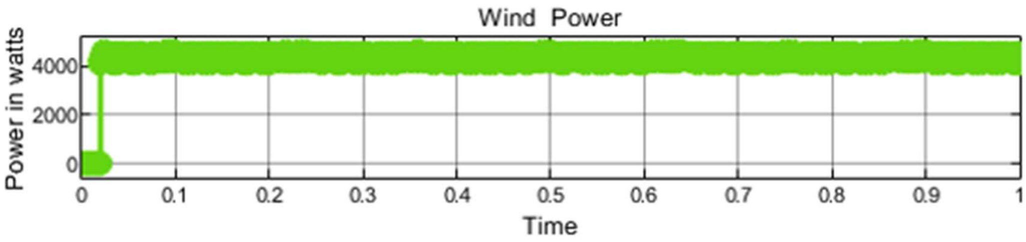

Figure 4.2 Output of the wind power

As observed from the results,the wind power is generating 4000 W and the wind speed is 12m/sec.

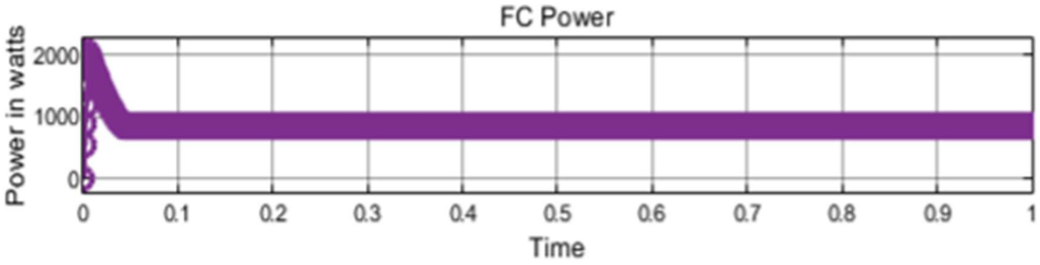

Figure 4.3 Output of the fuel cell

The fuel cell generates a maximum output power of 1000 W or 1 kW. Correspondingly, the performance of the battery in terms of different parameters such as state of charge (SoC) of the battery for different time intervals are shown in figure 4.4.

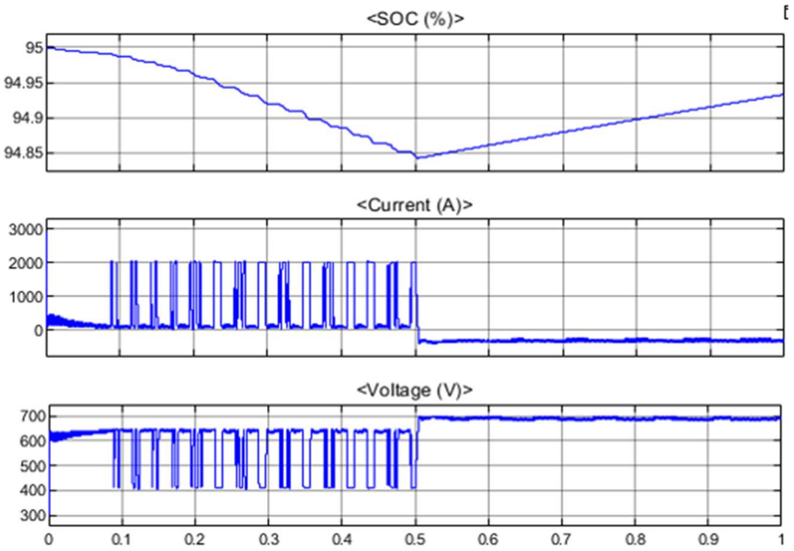

Figure 4.4 Output of battery power

It can be observed from figure 4.4 that, up to 0.5 sec during high load condition the battery discharges to compensate for load. After 0.5 secs during the low load condition, the current also reverses its flow during less load condition and the battery charges itself to observe SOC as shown in the above figure. The performance of the DC DC converter as step down transformer is shown in figure 4.5.

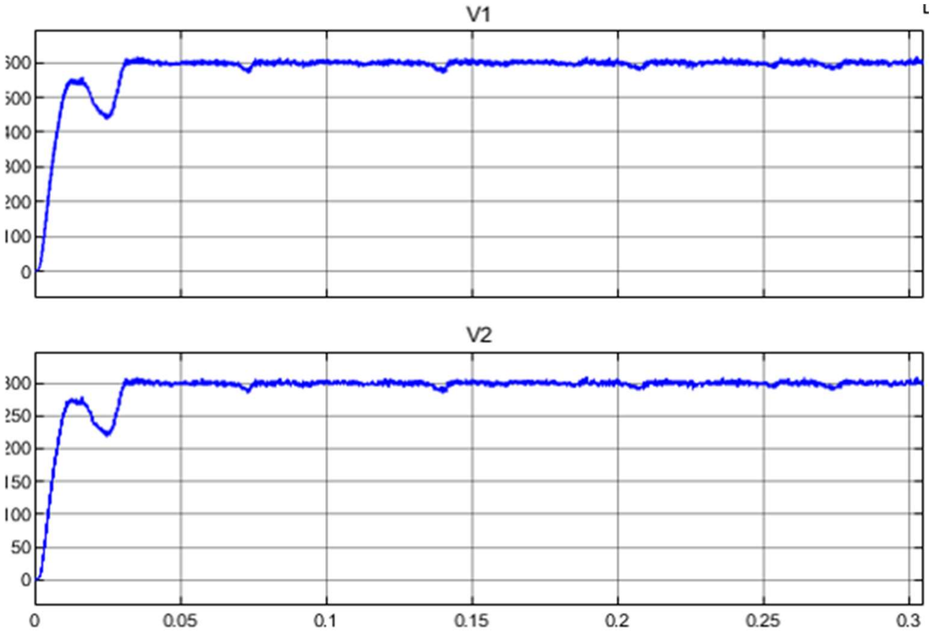

Figure 4.5 DC DC converter as a step down transformer

The DC DC transformer acts as a step down transformer when the voltage V_1 is greater than V_2 by transferring the power to V2 and vice versa. The output of the RES in terms of voltage and current are illustrated in figure 4.6.

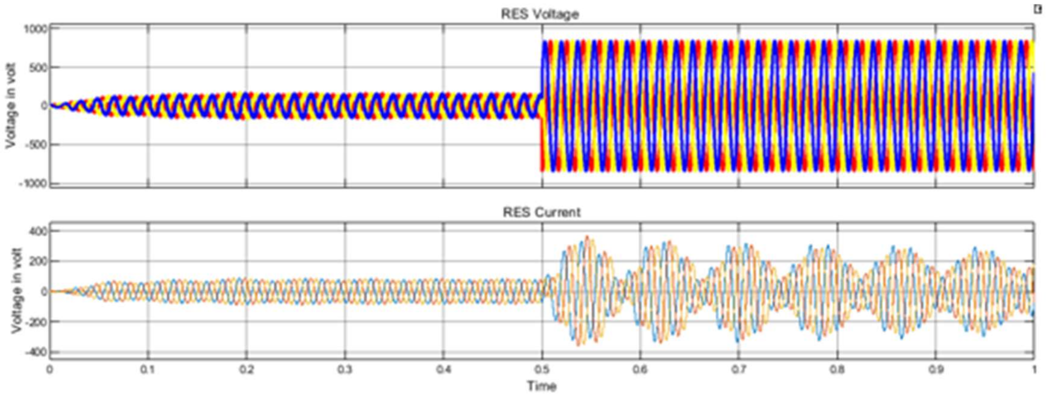

Figure 4.6 RES output

The variations of the RES voltage and RES current is shown in figure above. Irrespective of changes in the load, both the voltage and current are nearly constant and are in phase with each other. The RES transfers the energy to the grid during low power conditions and after 0.5 sec the load is less and hence the generated power is transferred to the grid.

5. Conclusion

This paper presents a smart transformer based control approach for controlling the power in the grid system. The distribution generation system used in this research consists of a PV system, wind energy system and fuel cells as energy generation sources and a battery for energy storage. An ANFIS based MPPT controller is used for extracting maximum power from the solar irradiation. The proposed approach was simulated in a MATLAB/SIMULINK platform. It can be inferred from the results that there is an effective control over the output of the grid and load. Both the voltage and currents of the RES are in phase with each other which further strengthens the effectiveness of the proposed approach.

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