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Design and Implementation of a Solar Panel Inverter as STATCOM Compensator

Mutaz Alnahhas and **Abdul Wali Abdul Ali***

Centre for Electric Energy and Automation (CEEA) Faculty of Engineering, Multimedia University, Cyberjaya, Malaysia

*Corresponding author: walikdr17@gmail.com

Abstract: A power system suffers from different losses, which can cause tragic consequences. Reactive power presence in the power system increases system losses and distorts the voltage. As a result, many researches are concerned with reactive power compensation. Moreover, reactive power should not be transmitted through a transmission line to a longer distance. Thus, Flexible AC Transmission Systems (FACTS) devices such as static synchronous compensator (STATCOM), static volt-ampere compensator (SVC), and unified power flow controller (UPFC) are utilized to overcome these issues. The necessity of balancing resistive power generation and absorption throughout a power system becomes a big concern in the electrical systems for reactive power compensation. Static synchronous compensator STATCOM is a shunt device used for the generation or absorption of reactive power as desired. STATCOM provides smooth and fast compensation and power factor correction. In this work, a solar Static synchronous compensator takes the DC input from the solar panel and inverted utilizing an H-bridge inverter. This topology is used for reactive power compensation and power factor correction at the load side. The simulation was done using MATLAB Simulink simulation tools. The system model was built using a single solar array for DC input and controlled using perturbation and observe method to maximize its power output. The STATCOM model was built using for high power MOSFETs to perform H- bridge inverter. The STATCOM was controlled using a hysteresis band current control using a PI controller to inject the current into the system. A hardware prototype of STATCOM was built and controlled using an Arduino microcontroller. The simulation results have demonstrated the STATCOM model of reactive power compensation and correcting the power factor under different loads of conditions. It also highlighted the proportional relation between reactive power presence and the increased cost of electricity bills. The proposed smart meter of STATCOM gives accurate reading and measurement. Overall, the simulated results showed a satisfactory level of compensation of reactive power and power factor correction. The system contained three significant parts; solar array, H- bridge inverter, and the PI controller. The smart meter circuit was capable of displaying readings regarding input solar voltage, current, and power factor on the LCD screen.

Keywords: Power factor, STATCOM, Controller, Inverter, Compensator

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1. INTRODUCTION

Electrical energy is the spine of an industrial era. An era that is derived by maximizing production efficiency and lowering the costs of manufacturing. In recent years, renewable energy sources play an essential role in electric power generation and its exponential growth due to environmental concerns. Therefore, integrating renewable energy systems into the grid will increase the ability to emission reduction and energy efficiency [1-3]. The power quality, voltage stability, and power factor become a major area of interest with increasing renewable energy penetrating the grid. Power factor correction is a practice followed by engineers around the world that will increase efficiency and capacity and lower the electrical power costs of the electrical systems. A PF close to unity is desired in the industries and it is achieved by increasing the percentage of the apparent power transmitted. Reactive power is essential to the operation of the motor, as it is used in the magnetization of motor windings [4-6]. However, the reactive power importance is undeniable. However, it is considered as an extra burden on transmission and distribution systems [7-10]. In this paper, a version of H- bridge inverter is used as a voltage source converter to work as Static Synchronous Compensator (STATCOM). The inverter is implemented to convert the DC solar power to AC. The VSC will be used to generate the needed reactive power or absorbing reactive power to the load. Power factor and voltage stability are improved by using the STATCOM; controlling the STATCOM is another challenge that is encountered during the design process. A PI controlling method being used in order to obtain the desired response. Overall, the reactive power compensation helps to improve transmission efficiency and increase the voltage stability.

The presence of reactive power is considered a loss of active power, which is supposed to be delivered to the loads. Therefore, the generation units will start to generate more power to substitute the loss of the reactive power. This event causes overall loss to the distribution networks and overloading on the transmission line. The power utility companies had concerns about reactive power loads, and they tend to maintain high-quality power delivery. This project describes a Simulink STATCOM model and studying the efficiency of the STATCOM as it is not required capacitor or inductor for power compensation. The lack of dynamic monitoring of the power system is a matter of concern as it helps the consumers the overall performance of the system and consumption [11].

2. SIMULATION MODELLING

The H-bridge inverter circuit was built using the Matlab-Simulink Simscape power system library, as shown in Figure 1. The main circuit components are four power MOSFETs getting triggered by a pulse generator, a DC capacitor link to maintain 24V input to the inverter, three windings linear transformer to convert DC 24 V to AC 240V. The loads are simulated with four RL loads 600, 800, 1000, 1500-Watt ratings. The inverter receives the gate signals from the hysteresis band generator and comparator.

Figure 2 shows the full Simulink block diagram of the system used to simulate STATCOM as an inverter. The model comprises four parts; the PV array circuit, the H-bridge inverter unit, the measurement unit, and the controlling unit. The solar unit supply 24V DC using two solar modules connected in series. H-bridge inverter is getting input from the solar and converter to 240V AC. All the voltages are the same at the inverter and grid side, using a phase locked loop to match the frequency and phase angle. The controlling unit will maintain that the reference current and injected current tracking each other. Four different loads have been tested on the model to check the power factor.

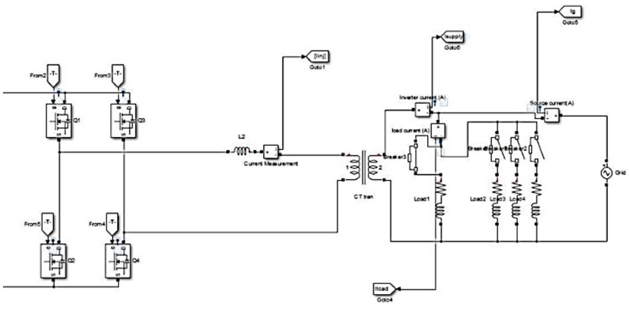

Figure 1. H-bridge Inverter Model

Figure 3 shows the complete Simulink measurement and monitoring unit block diagram. The unit consisted of two power factor meters to measure the instantaneous power factor, real power, reactive power, voltage, and current. Two blocks were used to calculate the load and the supply real and reactive power. The results are displayed using scope blocks to monitor the signals and the value of the waveform, respectively.

2.1. Control Unit Strategy

Many ways can vary the generated reactive power by the STATCOM. All the methods ultimately change the inverter output voltage (Vo). In this project, current in the STATCOM branch is taken as a reference to be controlled. This powerful method knows as Hysteresis Band Current Control. Figure 4 shows the full block diagram of the Simulink design of the control unit. The working operation of it to maintain a 24V DC bus voltage. If the DC voltage is lower than 24V DC, the magnitude of the current drawing's active components should be increased.

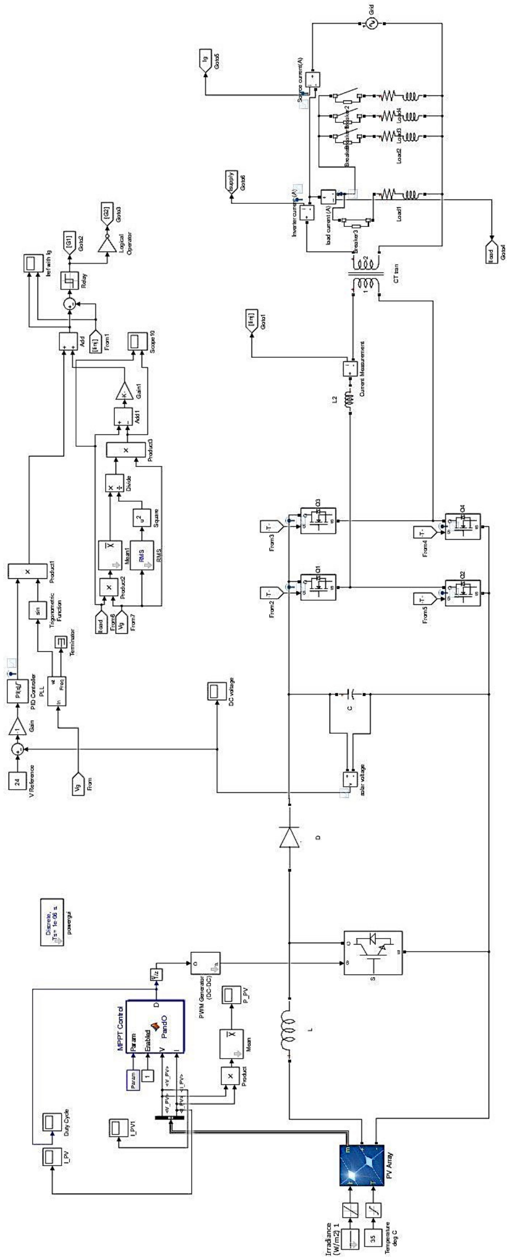

Figure 2. Full simulation model of Solar STATCOM

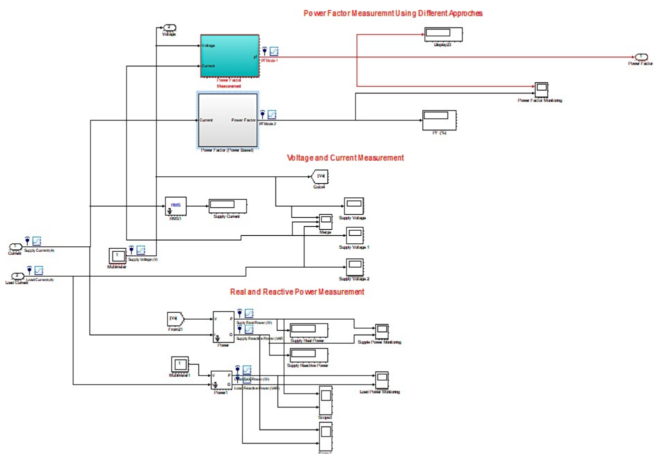

Figure 3. Overall Measurement and Monitoring model

However, the injected current is taken positive as a convention, and that's the gain of -1 been used. The difference is passed to the PI controller, which adjusts the current to maintain the 24V DC bus voltage. The active component of voltage and current should be in phase, Vg is measured, and the magnitude of current and sine of phase are multiplied. The inverter unit should also supply reactive power to the load demand. The lower parts of the figure helps to calculate the reactive current. Adding both components will result in the reference current, which should be injected by the inverter.

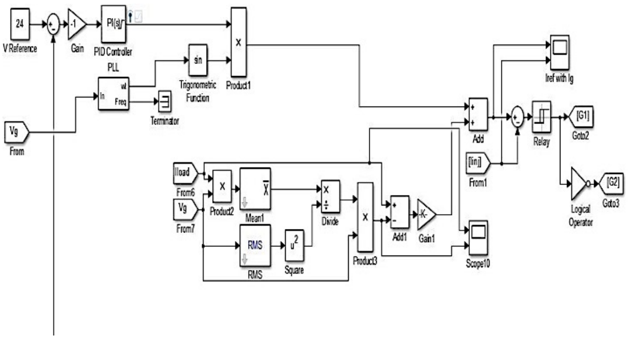

Figure 4. Control Unit Diagram

2.2. Reactive and Active Component Generators

Figure 5 shows the block used in the design to calculate the reactive component of the load current which is used by the I_{ref} . This block sense the load voltage and current to calculate the reactive power and the RMS value of the load voltage. Thus, the reactive component of the load current will be calculated using the following equation.

$$I_q = \frac{Q}{V} \tag{1}$$

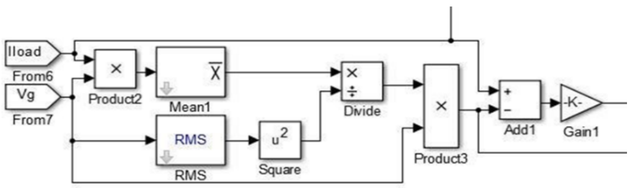

Figure 5. Iq Generator block

This active component shown in Figure 6 is designed to calculate the current drawn by the STATCOM used by the Iref. The voltage output of the solar, 24V DC, is sensed and compared with the reference voltage to obtain the error signal. The error signal is pushed to the PI controller to generate the current drawn by STATCOM branch. This output current is fed to the $I_{reference}$ generator.

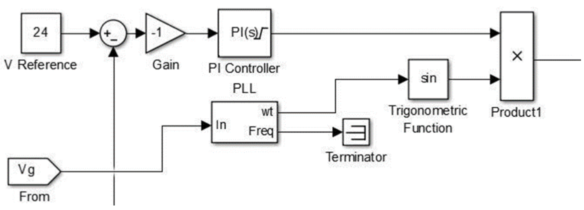

Figure 6. Active component block

2.3. Solar Power Unit

Figure 7 shows that the solar power unit's full model design, which consists of a PV array with module maximum power of 336 W, two parallel strings were used. Allowing proper modelling of an array of existing PV modules available from the NREL System Advisor Model as well as predefined PV module. The maximum power point tracker MPPT is used to acquire the solar PV module's maximum power and impart it to the grid. A non-isolated DC-DC converter (step-up/step down) is used to convert the network's maximum power. The DC-DC converter acts as an ally between a load and a PV module by fluctuating the ratio of duty 38 cycles. The impedance of load as it appears by the source is changing and coordinated at the peak power to convert the maximum power. The maximum power point tracker method is mandatory to keep the PV array working at its MPP. Many MPPT ways are being used to control the maximum power [3-15]. A Perturb and Observe (P&O) method is being used, which is the most popular method due to the simplicity of the feedback arrangement and less measured parameters [16-20].

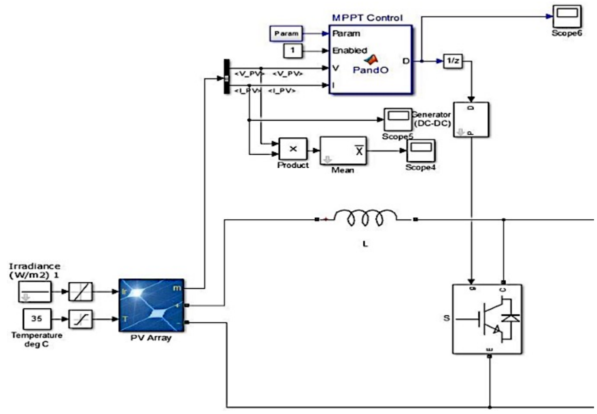

Figure 7. Solar Power Unit model

2.4. DC-DC Converter Analysis

In this design, a buck converter is being used to regulate the voltage since the output voltage is lower than the input voltage. The buck converter consisted of a diode 39 connected in parallel with the voltage source, a capacitor and the load, which represent the output voltage. A switch has been connected between a diode and a voltage source of the input and an inductor is connected between a diode and a capacitor. Figure 8 shows the simple buck converter diagram. Figure 9 shows the DC conversion ratio of the converter.

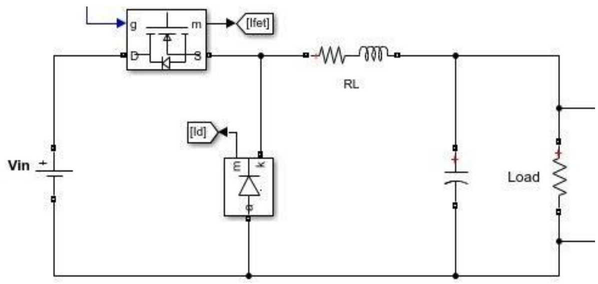

Figure 8. Basic buck converter diagram

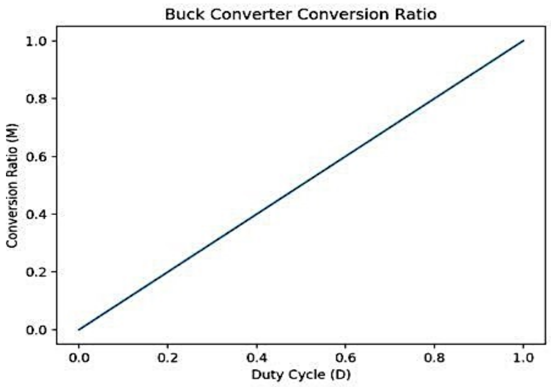

Figure 9. Buck converter DC conversion ratio

2.5. MPPT Control Algorithm (P&O) Method

Figure 10 shows the flow chart of the algorithm for multiple numbers of cycles. When a stable condition occurs, the algorithm will oscillate around the peak power to keep the power levels small, causing the perturbation size to remain insignificant. In this technique, the module's reference voltage needs to 41 be set, resembling the module's peak voltage. A PI controller is also used to set the voltage of the modules. This perturbation will cause some power loss and difficulties to imprint the maximum power under fast-changing atmospheric conditions. However, such a technique remains extremely simple and adaptable.

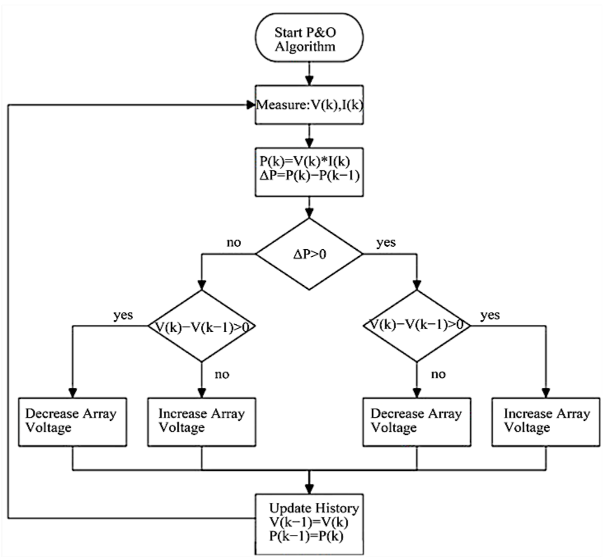

Figure 10. P&O algorithm flow chart

2.6. Hardware Implementation

Figures 11 and 12 show the hardware design and prototype, the component used, and their respective ratings. Two different implantations attempt on the hardware to get the best results of building an H- bridge inverter as STATCOM Firstly, the main components of the STATCOM hardware included four MOSFETS, two 4n37 optocouplers, a voltage sensor, a current sensor, DC voltage sensor, ZigBee communication Model, LCD, H1AA1 zero-crossing detection chip, solid-state relay, and Arduino Nano microcontroller, centre-tapped transformer.

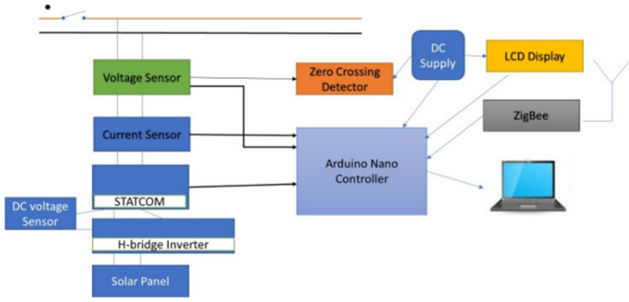

Figure 11. The Basic Architecture of the STATCOM hardware model

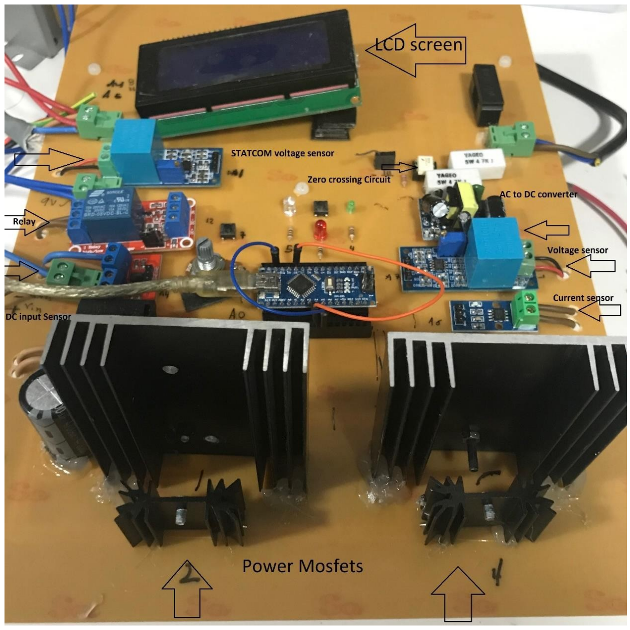

Figure 12. Full STATCOM prototype with Zero crossing

3. RESULTS PRESENTATION

In this section, the simulation of STATCOM results as well as H-bridge inverter hardware with the smart meter, compared and discussed.

Before incorporating the STATCOM model into the design, a breaker been placed on the inverter output and simulate to take the readings for different load condition of the loads, power factor, real power, reactive power and current comparison with the injected current by the STATCOM as shown in Figure 13. Figures 14 and 15 show that the load and grid current without the operation of the STATCOM with four different loads.

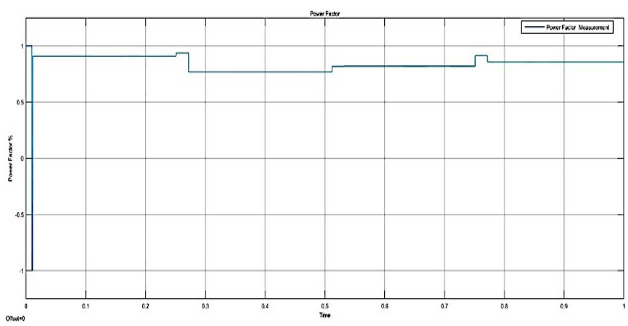

Figure 13. Power factor Model before incorporating STATCOM

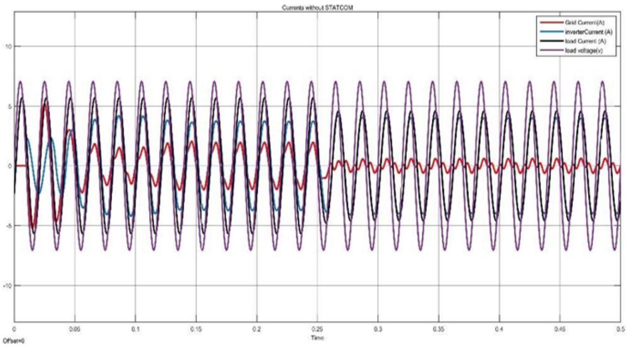

Figure 14. Currents waveforms without STATCOM

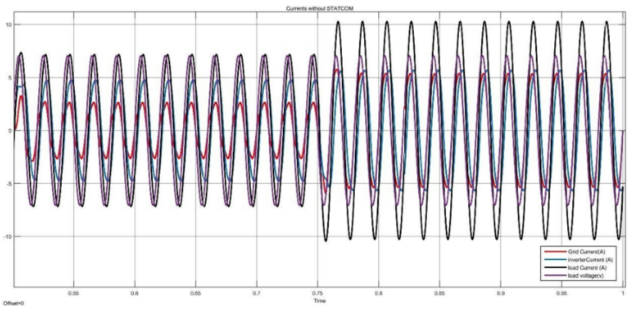

Figure 15. Current waveforms for the second two loads

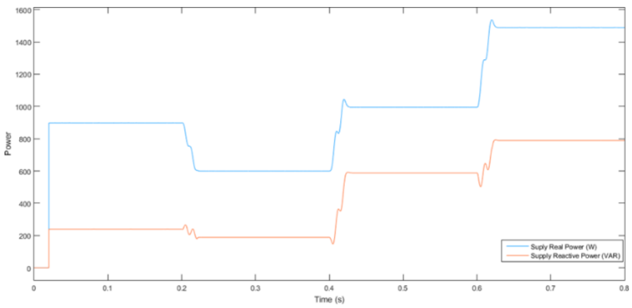

Figure 16. Grid active and reactive power without STATCOM

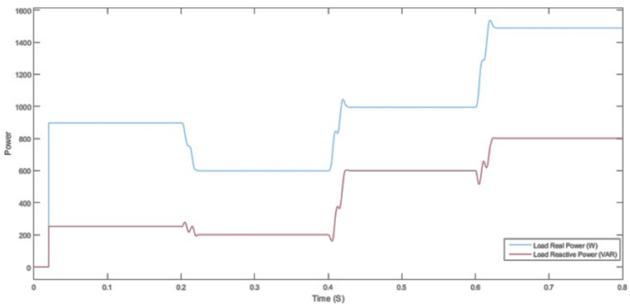

Figure 17. Loads active & reactive power without STATCOM

Figures 16 and 17 show the reactive power on the load side is similar to the grid side, which is expected due to the absence of power factor correction at the load side. Figure 18 shows the output voltage of the STATCOM, and it is synchronized with the grid and load voltage as 340V AC peak to peak. Figure 19 shows that the grid voltage and current with STATCOM connected to the system. The voltage and current are in phase with each other. Whenever the loads changes, the magnitude of the grid current changes but it is always in phase with the grid voltage. The STATCOM branch is supplying the loads whenever the reactive component of current is needed. Figure 20 shows the load voltage and current waveforms. It is seen that the voltage is leading the current due to the inductive load. It consumes both reactive and active power. Figure 21 shows the waveforms of the STATCOM branch current. It clearly shows that the actual current through the STATCOM branch within the band, it tracks the reference current with the same amplitude. The magnitude of the current through STATCOM branch changes whenever loads changes to meet the desired reactive component of the load current.

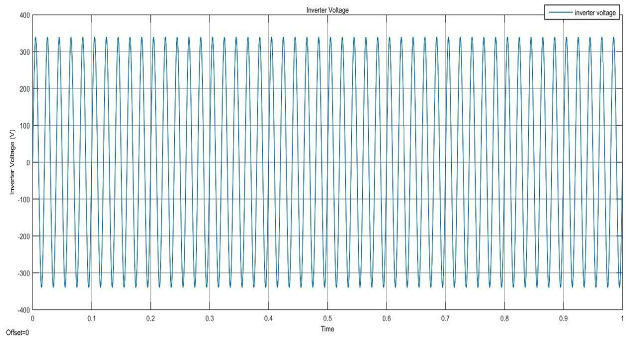

Figure 18. Inverter output voltage

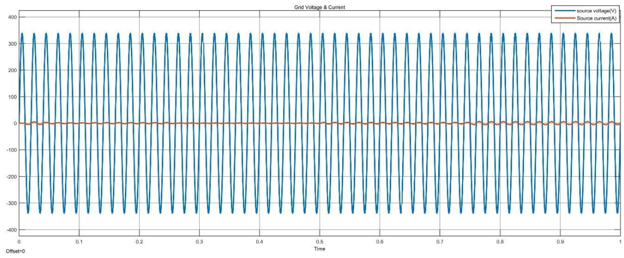

Figure 19. Grid voltage & current

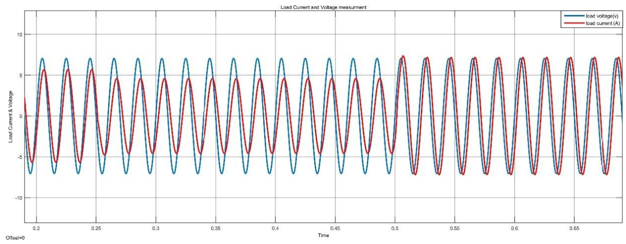

Figure 20. Load voltage & current

Figure 22 shows that the active and reactive power waveforms of the grid, STATCOM and load side. It can be seen that the grid is supplying only active power. The reactive power was supplying by the STATCOM for compensation with loads varying.

However, it is consuming a minimal amount of reactive power to compensate for the losses in the STATCOM branch. The varying loads are requiring both active and reactive power; the grid supplies additional active power while STATCOM generates additional reactive power. Figure 23 shows an improvement in power factor after the STATCOM inject current. For loads 1 and 2, the achieved power factor in almost one and close to unity, while loads 3 and 4, the power factor is around 0.94 due to high reactive power loads. Figure 24 shows the power factor before, and after STATCOM, the power factor improved on the first two loads which are closed to unity power factor, while before injecting the current the power factor was low and almost 0.88 on the first two loads.

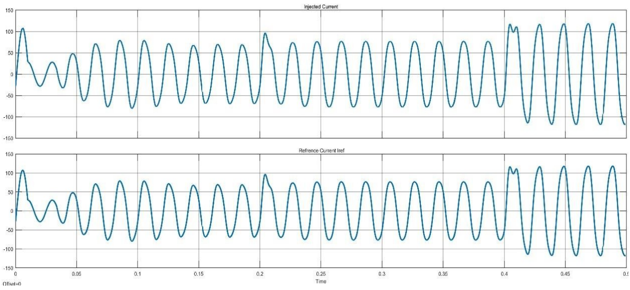

Figure 21. Current through STATCOM Branch and Hysteresis

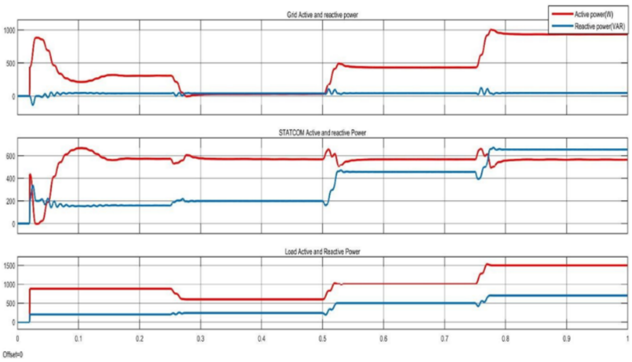

Figure 22. Active(red)& Reactive(blue) power through Grid, STATCOM &load

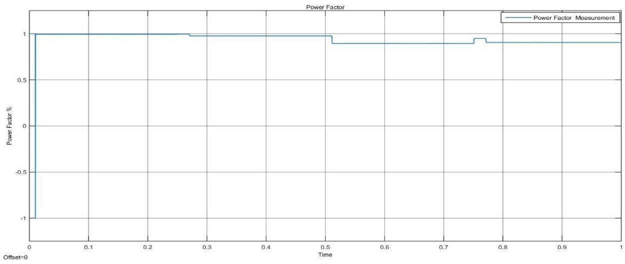

Figure 23. Power factor after STATCOM

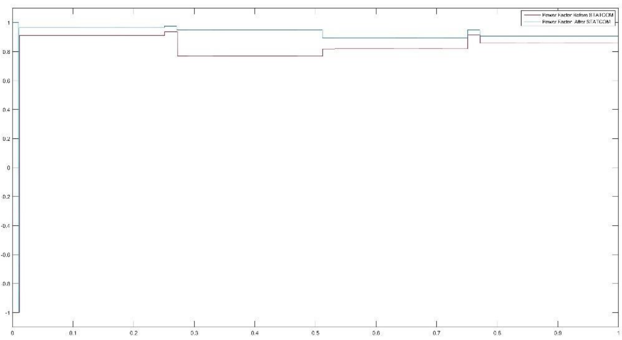

Figure 24. Power Factor Comparison

Figure 25 and 26 shows the waveforms with STATCOM while all currents are in the same phase with each other; the load current amplitude is taking the current from the grid and inverter to be added together. Figure 27 shows that the output power of the solar array as the module power rating 336W is being used in the system.

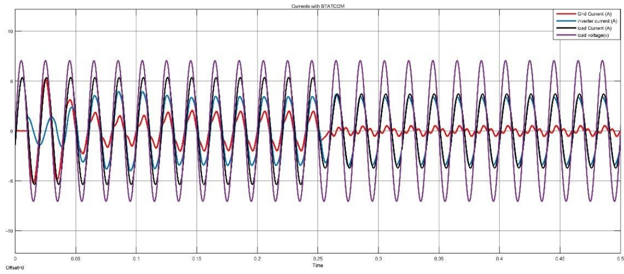

Figure 25. Currents with STATCOM for the first two loads

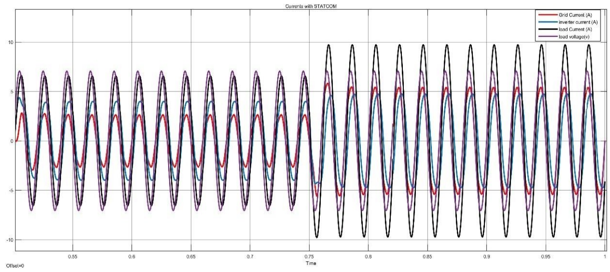

Figure 26. Currents with STATCOM for the second two loads

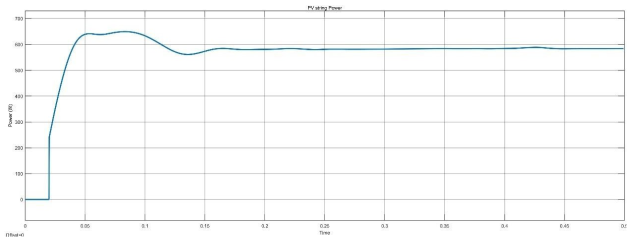

Figure 27. PV array output power

3.1. Hardware Results

The prototype contained two modes of operation. The first one can make manual adjustment of the inverter output voltage using potentiometer with the same phase and frequency of the grid. While the automatic mode will be based on the voltage sensor on the load and inverter voltage output, as the sensor compares the voltage and phase angle. The STATCOM will inject current based on the load if the load voltage lower than STATCOM the exchange of reactive power between the inverter and the load is achieved.

If |V0| > | VS|, then the inverter generates the reactive power. If |V0| < | VS|, then the inverter consumes the reactive power. If |V0| = | VS|, then there is no exchange of reactive power.

The prototype contains two relays for safety and protection purposes, the fist relay rated at 10A in the DC solar side as it open whenever the system requires more than 3A to protect the power MOSFETs. The second one to protect on the load side when the system voltage very low, it also could let the system to work as an inverter without load compensation.

Figure 28 shows the voltage source output with no load connected. The waveform does not show a pure sine wave due to the absence of using a filter. However, the bandwidth of the voltage can be controlled in order to vary the voltage whenever needed to be compared with the load voltage.

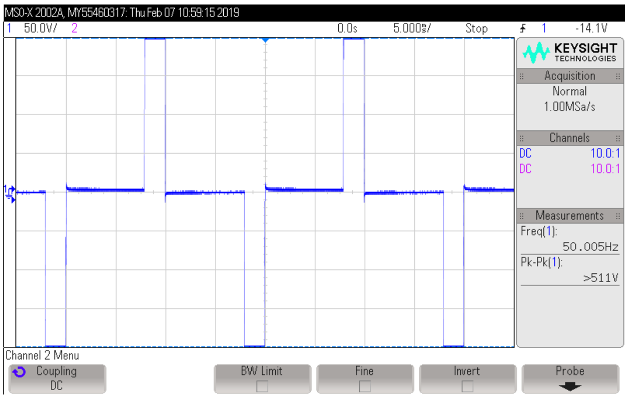

Figure 28. STATCOM inverter output waveform

Figure 29 shows the zero-crossing detector waveform with the same frequency as supply voltage, STATCOM, grid and load voltage all are synchronized at the same frequency and voltage amplitude of 340 V peak to peak. Figure 4.22 shows both waveforms of the zero crossing and inverter output voltage with 50Hz frequency whenever the amplitude of the voltage changes on the inverter side the zero crossing will keep following the phase angle of it.

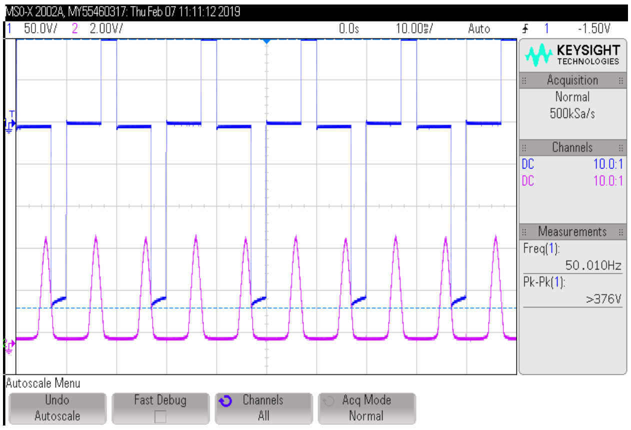

Figure 29. Grid and inverter voltage synchronization of frequency

4. DISCUSSION OF FINDINGS

The use of STATCOM plays an essential role in power factor correction and reactive power compensation. The reactive power drawn by inductive loads can lead to overloading events at different areas of the power system resulting in performance deficiencies and instability of the power system. However, the reactive power issue may not be of concern to the residential consumer as the majority of utility companies do not impose penalties on residential or commercial consumers for the excessive reactive power but, it would be a matter of concern when it comes to reducing or minimizing their electric bills. Furthermore, the power factor is defined as the ratio of real power to apparent power, considering this definition, it can be concluded that the power factor is inversely proportional to apparent power. Consequently, any increase in power factors results in a decrease in apparent power, whereas a decrease in the power factor causes an increase in the apparent power.

The consequences of excessive reactive power presence in the power system and found different ways to overcome these effects. The proposed Simulink STATCOM model is capable of power factor correction and reactive power compensation to keep the power factor close to unity with different loads of conditions.

Although the excellent performance of the STATCOM model, harmonics were presents which is an undesired event. However, presence did not affect the compensation and power factor correction process.

5. CONCLUSION

STATCOM based voltage source inverter from solar power model was built and modelled using Simulink for reactive power compensation and power factor correction. The Simulink simulation results show the effectiveness and the flexibility of the STATCOM in compensation of reactive power topology. Hysteresis band current control shows the effective control over the operation of STATCOM.

The smart meter prototype used for power monitoring were compared with a different type of meters. The meter has the capability of showing the total needed parameters, for instance; energy consumption, DC input voltage and current, real power, reactive power and power factor. This meter can send data to the end-end user for self-monitoring purposes using ZigBee communication; this meter provides efficient and accurate readings. It is also flexible and expandable as many other functions could be included.

The STATCOM prototype was designed using Eagle software. The STATCOM hardware-based VSC, combined with an Arduino, resulted in an excellent control results in terms of varying the voltage to the load. Circuit hardware was successfully tested under different types of load to ensure the stability of the system. The tracking of the voltage using the zero-crossing detector is obtained in the hardware.

Overall, the simulated system proved the controlling of the current injected to different types of load and controlling the power factor despite the presence of a high THD. The system contained H-bridge inverter taking the DC input from a solar array it proved to do the compensation to the system from the current produced. The circuit of the smart meter was capable of reading and displaying the parameters of PF, P, Q, I and V while monitoring the input voltage and current from the solar system using an LCD screen.

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REFERENCES

[1] N.G. Hingorani, L. Gyugyi. Understanding FACTS, Concepts and Technology of Flexible AC Transmission Systems. IEEE Press 2000.

[2] G. Saikrishna, “Hardware Implementaion of 10w PV Panel as STATCOM Voltage Compensation in a Daytime Distribution Utility,” pp. 2–5, 2015.

[3] Y. Wei, B. Cao, Y. Li, and S. Dai, “Research on Full-Bridge Static Compensator with Small-

Capacitor Equipped and Its Application," vol. 1, no. June, pp. 27–29, 2017.

[4] T. Isobe, L. Zhang, H. Tadano, J. A. Suul, and M. Molinas, "Control of DC-capacitor Peak Voltage in Reduced Capacitance Single-Phase STATCOM," no. 1, 2016.

[5] T. P. Enderle, C. Fischer, R. C. Beltrame, V. F. Montagner, C. Rech, and P. Electronics, "D-STATCOM Applied to Single-Phase Distribution Networks: Modeling and Control," pp. 321– 326, 2012.

[6] C. Tareila, P. Sotoodeh, and R. D. Miller, "Design and Control of a Single-Phase D- STATCOM Inverter for Wind Applications," 2012.

[7] Y. Horita and N. Morishima, "Single-phase STATCOM for feeding system of Tokaido Shinkansen," pp. 2165–2170, 2010.

[8] M. Davies, P. J. Fitz, and K. E. Owen, "Static VAr compensator (STATCOM) based on single- phase chain circuit converters."

[9] A. W. Abdul Ali and A. Alquhali, "Improved Internal Model Control Technique for Position Control of AC Servo Motors", *ELEKTRIKA- Journal of Electrical Engineering*, vol. 19, no. 1, pp. 33-40, 2020.

[10] R. Cimbals, O. Krievs, and L. Ribickis, "A Static Synchronous Compensator for Displacement Power Factor Correction under Distorted Mains Voltage Conditions," vol. 4, no. 4, 2011.

[11] P. Sotoodeh and R. D. Miller, "A New Single-Phase Inverter with D-STATCOM Capability for Grid-connected Small Wind Turbines," no. Mmc, pp. 175–179, 2013.

[12] H. Hafezi, "Assessment of Two Different Reactive Power Estimation Methods on Single Phase Loads," pp. 82–87, 2014.

[13] H. Hafezi and A. Balikci, "Cascade PI Controller for Single-phase STATCOM," vol. 2, pp. 88–93, 2014.

[14] Z. Xi, B. Parkhideh, S. Bhattacharya, and N. Carolina, "Instantaneous Phase-Locked Loop for Performance Improvement of Power System with STATCOM under Single-line to Ground Fault," pp. 3750–3757, 2011.

[15] T. Nithin and E. P. Cheriyan, "FPGA based hardware implementation of solar PV inverter to act as STATCOM," pp. 4–9, 2017.

[16] R. K. Varma, S. Member, and E. M. Siavashi, "PV-STATCOM : A New Smart Inverter for Voltage Control in Distribution Systems," vol. 3029, no. c, pp. 1–12, 2018.

[17] W. Abdul Ali, F. Asmida and A. R. Nasri Hayima, " A Review on The AC Servo Motor Control Systems", *ELEKTRIKA- Journal of Electrical Engineering*, vol. 19, no. 2, pp. 22-39, 2020.

[18] D. Aiswarya and M. G. Nair, "A Comparative Performance Analysis of PV Grid Interface STATCOM Control Algorithms," pp. 1–7.

[19] K. Ilango, A. Bhargav, A. Trivikram, P. S. Kavya, G. Mounika, and M. G. Nair, "Power Quality Improvement using STATCOM with Renewable Energy Sources."

[20] K. Ilango, A. Bhargav, A. Trivikram, P. S. Kavya, G. Mounika, and M. G. Nair, "Power Quality Improvement using STATCOM with Renewable Energy Sources."