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Original Article

Performance Analysis of Hybrid Renewable Source RSC-MLC Module Integrated D-STATCOM with PQ Controller

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Abstract - *In this paper, "a conventional D-STATCOM (Distributed Static Synchronous Compensator) with a six-switch VSC (Voltage Source Converter)" connected DC link capacitor is updated; with a hybrid renewable source "RSC-MLC (Reduced Switch Count – Multi-Level Converter) module." The conventional D-STATCOM only compensates for reactive power, whereas this topology injects active and reactive power. The RSC-MLC module is a voltage regulating device with multiple sections connected in series. Each section can be connected to renewable sources like wind farms, solar plants, or batteries. The DC link voltage reference generator controls the module voltage. D-STATCOM is controlled by the most optimal control structure PQ (Active and Reactive Power) theory with higher harmonics mitigation capability. The complete test system with a three-phase grid feeding non-linear reactive power load compensated by hybrid renewable source RSC-MLC module integrated D-STATCOM with PQ controller is modeled in MATLAB Simulink environment. Performance and analysis of the proposed system are done using different tools from the software.*

Keywords - *D-STATCOM, Renewable source, VSC, MATLAB Simulink, RSC-MLC, PQ.*

1. Introduction

Power generation from renewable sources has become mandatory in new-generation power systems to avoid fossil fuel consumption. Due to depleting fossil fuel sources and avoiding environmental pollution, sustainable renewable energy sources need to be adopted. However, the power extraction from renewable sources and injection into the grid in synchronization to conventional sources for power-sharing to load is a difficult task. Along with renewable power-sharing, the quality of power also needs to be improved using FACT (Flexible Alternating Current Transmission System) devices like D-STATCOM [1], which can inject reactive power and reduce harmonics in source current. Many loads are connected in any power system, including "linear and non-linear loads." The power system has increased harmonics when the grid is operated with the non-linear load as these loads comprise power electronic devices, which are the major cause of generating harmonics in the grid. These harmonics introduced into the grid need to be filtered as they may damage the source or any other load connected in parallel.

Therefore, a D-STATCOM device is connected to a grid system comprising a six-switch converter with a DC-link capacitor operated using PQ theory [2]. The D-STATCOM module injects reactive power along with harmonics mitigation in a grid. The power factor of the source improves as the D-STATCOM device compensates for the reactive power needs of the load. PQ theory [3] is considered optimal control structure integration to D-STATCOM for harmonics mitigation. Therefore, this control scheme is adopted into our proposed test system. Along with reactive power compensation, the D-STATCOM can also inject active power when the DC link is connected with the DC source.

The DC source can be renewable, like PVA, wind farm, or battery [10] [15]. The DC source can also be a hybrid module with multiple renewable sources sharing power. For this, an RSC-MLC renewable source module shares the wind farm, PVA, and battery power per the environmental parameters. Below is the proposed test system with non-linear load with shunt connection of RSC-MLC module [7] integrated D-STATCOM. The RSC-MLC module is connected with the main source as a PMSG (Permanent Magnet Synchronous Generator) wind farm and two PVA modules. In the event of the failure of renewable sources, the system is supported by a battery backup. Fig. 1 depicts the planned system in its entirety.

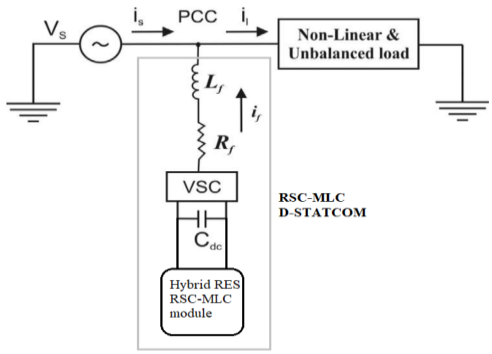

Fig. 1 Proposed test system with hybrid renewable source RSC-MLC module

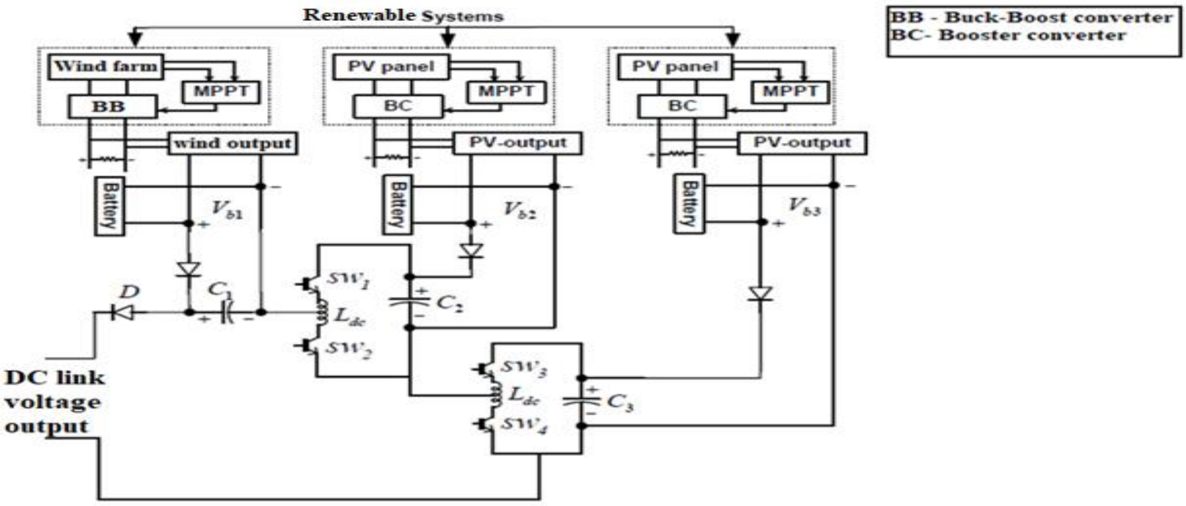

Fig. 2 RSC-MLC module with hybrid renewable sources

2. Modeling of RSC-MLC module

In the proposed system in the RSC-MLC module, one unit is a wind farm [4] connected buck-boost converter, and two are PVA-connected booster converters. Each unit is connected in parallel to the battery for a backup power supply. All the three units are connected in series through four controllable switches SW1-SW4 [7] which a DC voltage regulator controller controls. The module is a connection of two or more sources in series with high-frequency switches connected between the source converters to achieve different voltage levels [5] as per user demand. Three hybrid renewable source modules are connected with different operating voltages for our test system. The complete structure of the proposed RSC-MLC module is shown in Fig. 2.

The first module is a PMSG wind farm connected to a Buck-boost converter which is controlled by a power signal feedback "MPPT (Maximum Power Point Tracking) controller" [6]. The output of the buck-boost converter is connected in parallel with a battery storage unit which can share or store power during deficit and excess wind power [9] conditions, respectively.

The second and third units are PV panels connected to a conventional booster converter controlled by a "P&O (Perturb and Observe) MPPT controller." A battery storage unit is connected in parallel for power-sharing and storing with PV panels, even for the PV panel modules.

As multiple renewable sources are used, the RSC-MLC module is considered a hybrid. All the three source modules [10] (One wind farm and two PV panels) are connected to four switches (SW_1-SW_4) multi-level converters [8], which are controlled using a DC link voltage reference control structure. As observed in Fig. 2, two switches, IGBTs (Insulated-Gate Bipolar Transistor), are connected in series with an energy storage inductor in between them. Capacitors C_1, C_2, and C_3 are the output capacitances of the source modules. These capacitors are connected in series through the IGBT boosting inductors circuits [11], which can control the "DC link voltage output of the RSC-MLC module." To avoid reverse current conduction to the sources, series diodes are connected, which only allow power flow from the source to the DC link side.

As per the switching of the IGBT switches, the final DC link voltage [7] is determined as in table I.

Table 1

V_{dc} ref	Switching states	DC link voltage
<700V	SW_2, SW_4	Vb_1
700V – 766V	$SW_1(\delta_1)$, SW_4	$Vb_1+Vb_2*\delta_1$
766V – 832V	$SW_1(\delta_2)$, SW_4	$Vb_1+Vb_2*\delta_2$
832V – 898V	SW_1, SW_4	Vb_1+Vb_2
898V – 964V	SW_1, SW_3 (δ_1)	$Vb_1+Vb_2+Vb_3*\delta_1$
964V – 1030V	SW_1, SW_3 (δ_2)	$Vb_1+Vb_2+Vb_3*\delta_2$
1030V – 1100V	SW_1, SW_3	$Vb_1+Vb_2+Vb_3$

As per table I, the lowest DC link voltage is 700V, and the highest is 1100V. For these possible reference voltages, the first wind farm source to set with 700V output, and the other two PV panel sources are set with 200V each. Only the wind farm source will operate for the lowest voltage reference. All three modules are connected in series for the highest voltage reference, increasing the voltages generating 1100V. "For the middle voltages with a resolution of 66V, the switches (SW_1 or SW_3) are operated at high switching frequency with different duty ratios (δ_1 and δ_2). The fixed duty ratios of δ_1 and δ_2 are given as 33% and 66%, respectively [7]. The reference DC link voltage value is generated with reference currents ($I_c^*{}_{abc}$) generated by the PQ control theory of the D-STATCOM module." Below is the control of the reference voltage generator.

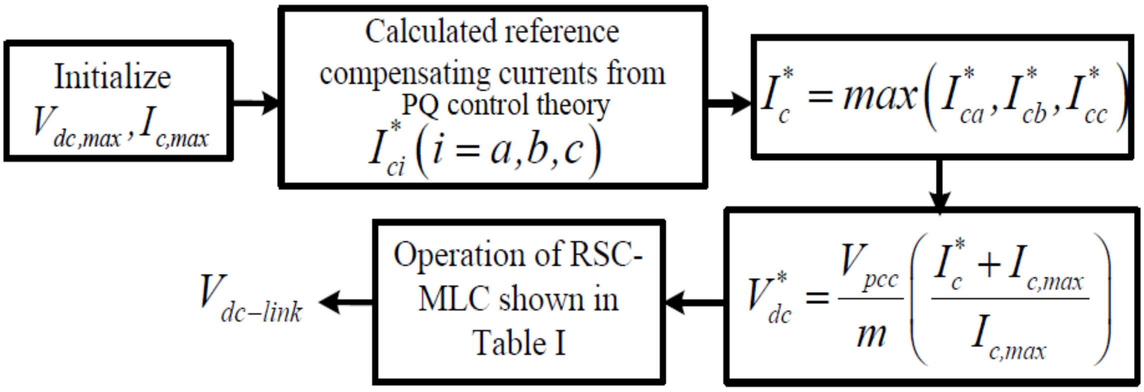

Fig. 3 Reference DC link voltage controller

The final reference DC link voltage V_{dc}^* is given as

$$V_{dc}^* = \frac{V_{pcc}}{m}\left(\frac{I_c^*+I_{c,max}}{I_{c,max}}\right)\text{...(1)}$$

Here, "V_{pcc} is the voltage magnitude at the point of common coupling of the grid test system, I_c^* is the maximum of (I_{ca}^* I_{cb}^* and I_{cc}^*), which are the reference current values generated by PQ [12] control theory, and $I_{c,max}$ represents maximum compensation current of D-STATCOM." The variable 'm' is the modulation index defined per the user to maintain the reference voltage between the 700V – 1100V range. The internal circuit topologies of the wind farm and PV panel modules, including the buck-boost converter and booster converter, are taken from [12].

3. D-STATCOM Controller Design

In addition to suppressing harmonics, the D-STATCOM injects reactive power into the grid, enhancing the source's power quality. This device is a reduced rating version of STATCOM (Static Synchronous Compensator) [13] installed in the distribution grid system; hence, the name suggests Distributed STATCOM. When the D-STATCOM device [14] is connected with a DC source on the DC side of the VSC, the module also tends to inject active and reactive power. It reduces power consumption by the load from the main source. Suppose the DC link is integrated with renewable source modules [15], as discussed in section II (Hybrid Renewable source RSC-MLC module). In that case, the D-STATCOM device can now inject renewable active and reactive power into the grid [16]. The conventional source power of the grid is now replaced with renewable sources making it a green energy system.

The D-STATCOM device combines six high-frequency operating power electronic switches connected to a single DC link capacitor. The interlink between grid and D-STATCOM is done through an inductive filter that reduces VSC's harmonics [22]. The D-STATCOM schematic can be seen in Fig. 4.

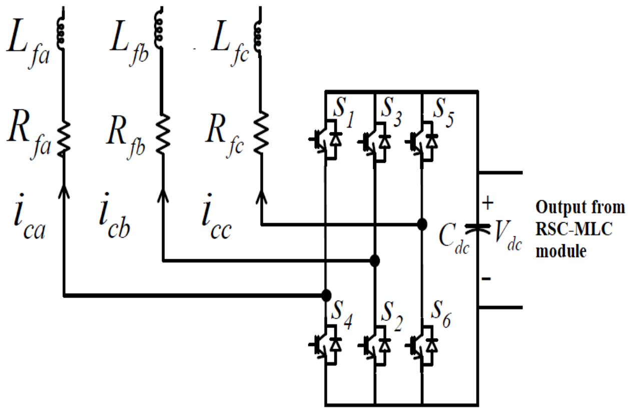

Fig. 4 D-STATCOM schematic

The six-switch VSC is controlled by different control algorithms like SRF (Synchronous reference frame) method, IRP (Instantaneous reactive power) or PQ theory, and DQ (Direct and Quadrature) theory [18]. From these techniques [18] [19], the PQ theory is considered the optimal control structure for D-STATCOM to operate with maximum harmonics mitigation [20] capability, and also the theory can help share active power from renewable sources. A comparative table determining the optimum controller for the D-STATCOM is given in table II.

Table 2. D-STATCOM controllers' comparison

Parameters	SRF theory	PQ theory
Reactive power compensation	Moderate	High
Response time	Slow	Fast
Controller complexity	Highly complex	Less complex
Number of sensors	More sensors	Fewer sensors
Harmonics mitigation	Lower harmonic mitigation	High harmonic mitigation

Fig. 5 depicts the PQ theory's control system.

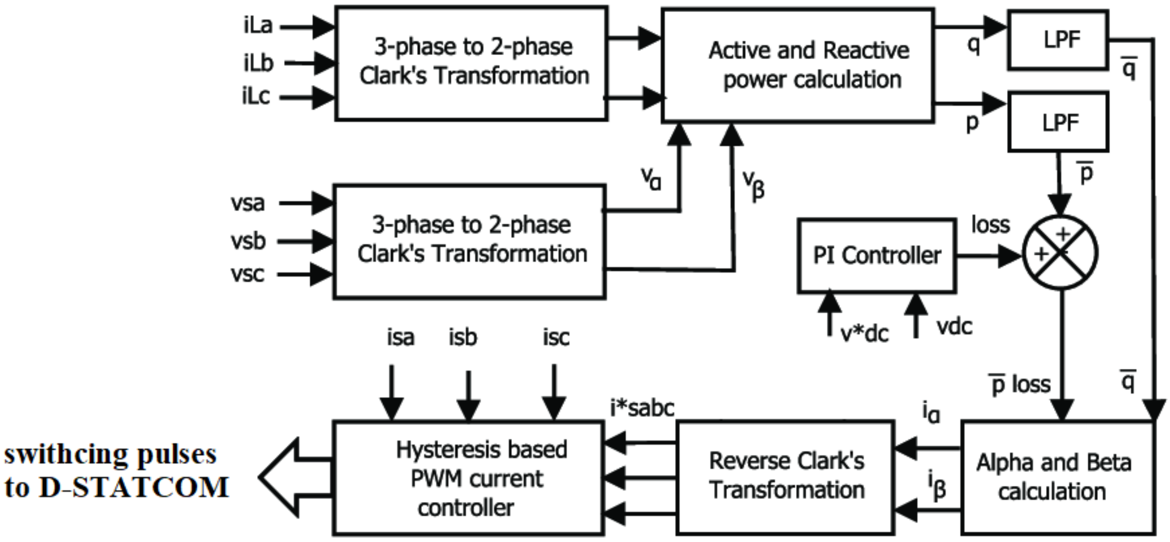

Fig. 5 PQ theory of D-STATCOM

The three-phase measuring signals are converted to two-component signals αβ by the below equations.

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \frac{2}{3} * \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \text{.....(2)}$$

In the given equation, the variable 'f' can be either voltages or currents. From the two-component αβ voltages and currents $(V_\alpha V_\beta I_\alpha I_\beta)$ the active and reactive powers of PQ are generated as

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \text{.....(3)}$$

These active and reactive power signals are filtered using a low pass filter, reducing disturbances in them for the better response of the controller. The active power component is added with the loss component, which is generated by DC [20] voltage regulator. The DC voltage regulator output is PI-controlled fed DC voltage error. The loss component is given as

$$P_{loss} = V_{dc}^* - V_{dc}\left(K_p + \int K_i . dt\right) \text{.....(4)}$$

The PI gains are set per the stabilization of D-STATCOM integration to the grid. These final filtered and updated $\overline{P_{loss}}$ and $\bar{Q}$ components are converted to two-component currents αβ, which is given as

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} P \\ Q \end{bmatrix} \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \text{.....(5)}$$

The two current components are converted to three-phase components Iabc as

$$\begin{bmatrix} I_a^* \\ I_b^* \\ I_c^* \end{bmatrix} = \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \text{.....(6)}$$

These current components are considered reference currents for the D-STATCOM compared to measured currents of D-STATCOM generating the error. This error is fed to the "hysteresis current loop controller" [23] for the generation of pulses for the six-switch inverter. A comparative analysis with different renewable sources connected with an optimal control scheme using simulation validations is given in section 4.

4. Simulation result analysis

As per Fig. 1, the test system with three-phase source, liner, and non-linear load, D-STATCOM with hybrid renewable source RSC-MLC module, is modeled in a Simulink environment. The controller for the D-STATCOM and reference voltage generator is also modeled using commonly used blocks of the library browser.

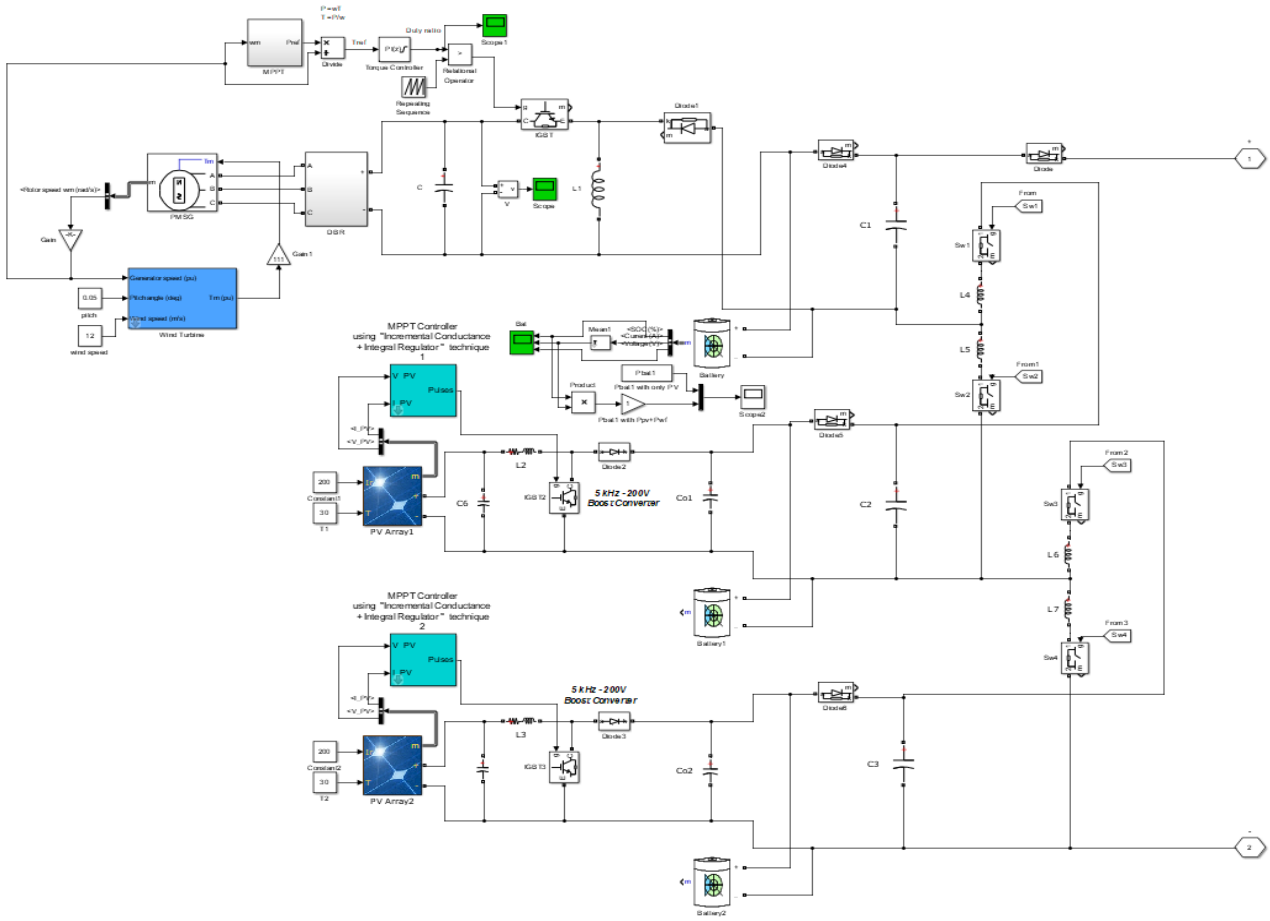

Fig. 6 Hybrid renewable source RSC-MLC module

The internal Simulink modeling of RSC-MLC with the wind farm, PV panel, and battery storage unit is shown above in Fig. 6. The "wind farm buck-boost converter" is controlled by power signal feedback MPPT, and both PV panel booster converters are controlled by incremental conductance MPPT. All three sources are connected to DC link through four switches RSC-MLC circuit.

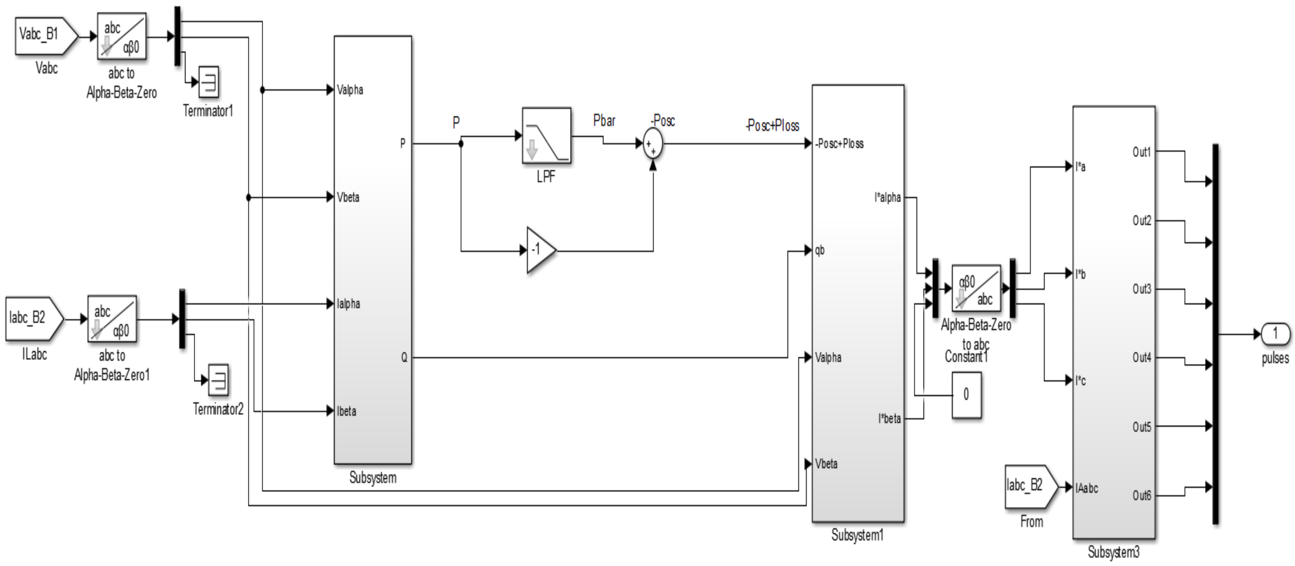

Fig. 7 PQ theory D-STATCOM controller

The above is the PQ theory control structure modeling generating switching pulses for D-STATCOM. The simulation of the above-defined system is run for 1sec, and the results are recorded without and with a D-STATCOM connection. Below are the "three-phase voltages and currents of the main source when the system operates without D-STATCOM."

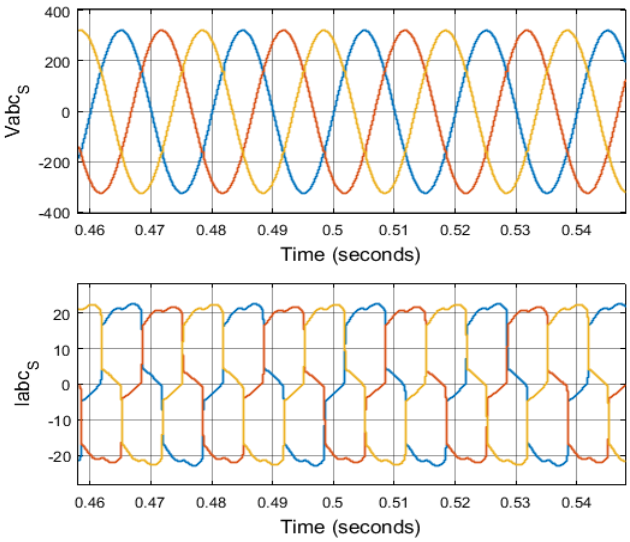

Fig. 8 Voltages and currents of the three-phase source without D-STATCOM

Since non-linear load consumption causes a high harmonic content in the source current, it may be seen. Fig. 9 shows the three-phase voltages and currents of the primary source when the system is coupled with D-STATCOM. These harmonics are attenuated to a very low amount.

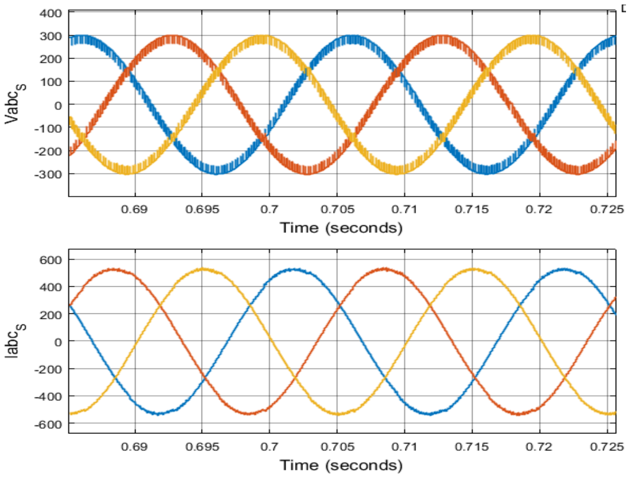

Fig. 9 Voltages and currents of the three-phase source without D-STATCOM

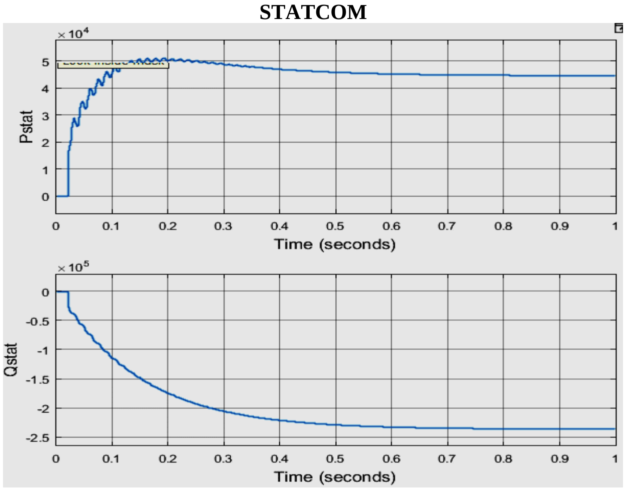

Fig. 10 Injected active and reactive power of D-STATCOM

The above graphical plot is the active and reactive power injected by the D-STATCOM, which can be noted as P=45kW and Q = 240kVAR. A comparative graph with active power injected with conventional only PV panel renewable RSC-MLC module and renewable hybrid wind farm PV panel module is shown in Fig. 11.

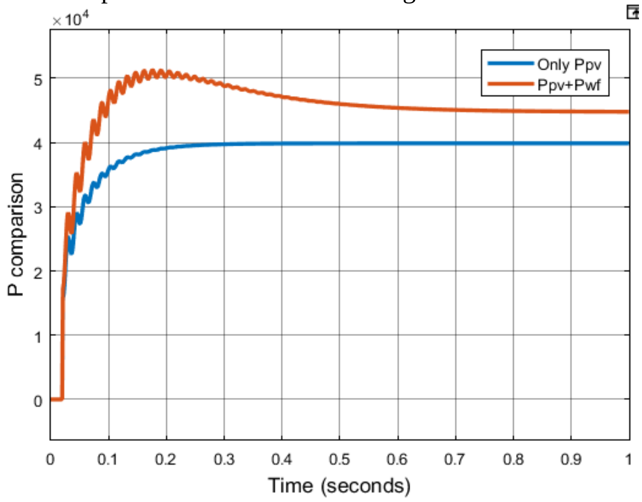

Fig. 11 Comparative active power with only PVA module and hybrid wind farm and PVA module

The power injected by the hybrid wind farm PV panel module is comparatively high at 45kW, and only the PV module is at 40kW. Due to the high-power generation of the wind farm for the same rating as the PV panel, the system is injecting more power into the grid. So, it is viable and optimal to use hybrid renewable sources rather than a single type of renewable energy power generation source.

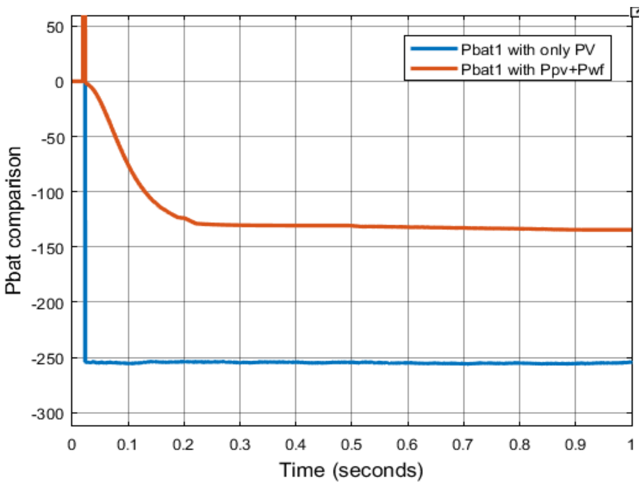

Fig. 12 Comparative battery storage power with only PVA module and hybrid wind farm and PVA module

For the same, the first source unit battery storage power comparison shows that the battery is storing more power for the hybrid module.

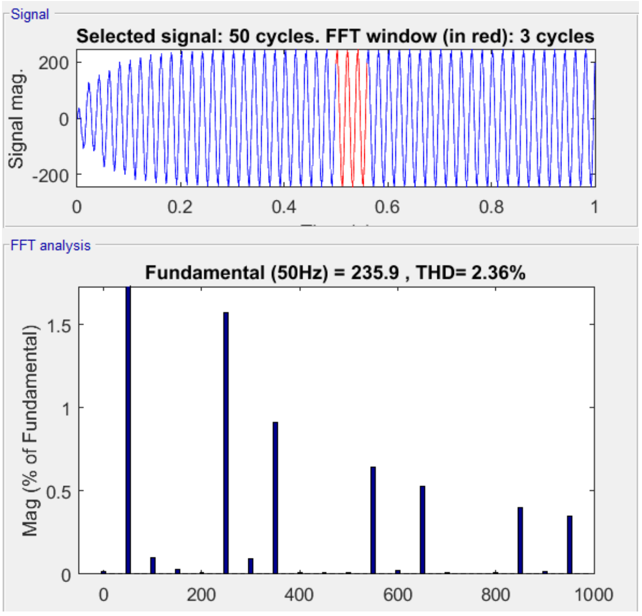

Fig. 13 FFT analysis of source current to determine THD

However, the THD of the source current for both the models is nearly the same as the PQ theory control structure is maintained the same in conventional RSC-MLC module and hybrid wind farm PV panel RSC-MLC module.

5. Conclusion

As per the above results validation of the proposed test system with hybrid wind farm PV panel RSC-MLC module integrated D-STATCOM, the grid receives more power from the renewable source for the same rating as the conventional module. A comparative analysis between conventional only PV panel RSC-MLC topology and novel hybrid wind farm PV panel RSC-MLC topology is done in this paper. It is determined that the power generated by the hybrid source is more than conventional single renewable source units with the same rating. As the wind farm's efficiency is comparatively higher than the PV panel, the power generated is also high, and more conventional fossil fuel is compensated. The THD of the source current is also maintained at 2.36%, which is acceptable as per IEEE standards. All the graphs are represented with time as a reference variable, generated by a powerful tool in Simulink.

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