Execution of advanced solar-shunt active filter for renewable power application

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Abstract
This manuscript proposes a novel Solar-shunt active filter (solar-SHAF) controller for improving the power flow in a larger power-application. The proposed fault and non-linear detection unit (FANDU) avails faster disturbance detection. A novel FAND regulator (FANDR) is suggested to disconnect the solar power generation from the considered system within 10–12 s and the total inverter capacity is used for providing reactive power support to compensate the power fluctuation. A solar active power regulator (SAPR) is proposed to restore the active power output of the solar plant in a ramp-wise manner after the successful damping of the power fluctuations. The restoration of rated solar power results offers a faster settling time in comparison to the standard grid code limits. The proposed approach is applicable for light, dark, and partial shading conditions. During the dark period, the total inverter capacity is used to compensate the power fluctuations and in partial shading conditions, the inverter is used to balance the solar power at its rated limit. The overall system is designed and tested through MATLAB software by considering different test conditions. It is analyzed that the suggested approach facilitates a significant improvement in power exchange on a 24/7 basis during the local and inter-area fluctuating mode.

1 INTRODUCTION

Due to the increase in energy demand, larger power generation stations with longer transmission lines are integrated for power transmission. However, the occurrence of fault/uncertainty affects the power flow and system performances. The generation of low-frequency power disturbances from the transient conditions is one of the major limiting factors for the overhead transmission line [1]. Traditionally, the above problems are solved using the synchronous generator (SG) based power system stabilizers (PSS) [1–3]. Conversely, as an improvement recently flexible AC transmission (FACT) based power electronic devices such as static synchronous compensators (SVC and STATCOM) [4–6], thyristor controlled series compensator (TCSC) [7, 8], series and shunt active filter (SEAF and SHAF) [9, 10] are chosen for the compensation of power fluctuations and power restoration in the existing power system.

To maintain the power deficit, larger renewable solar plants (excess of 100 MW) are installed nowadays. The larger plants including Bhadla Solar Park (1515 MW), Kurnool Ultra Mega Solar Park (750 MW), and Charanka Solar Park (690 MW) in India, Topaz Solar Plant (550 MW), Desert Sunlight Solar Plant (550 MWAC), and Carrizo Energy Solar Plant (177 MW) in the United States, and Longyangxia Dam Solar Park in PRC (850 MW) are installed [11–13]. Due to the huge penetration of renewable solar plants into the power system, there is a significant decrease in power system stability [14, 15]. Smart solar inverter topologies like constant power factor (pf), frequency, active and reactive voltage/power, low/high voltage/frequency ride-through (LVRT, HVRT, LFRT, and HFRT) [16] have been suggested and used for a larger renewable integrated system [17, 18]. In [19], a robust control approach is designed by combining both Solar-STATCOM for enhancing the power system performances during both light and dark periods and increasing the connectivity of wind plants in the dark period [20, 21]. By
using the above discussed proposed control algorithm, firstly the inverter capacity is used to fulfil the real power demand with power fluctuation damping and the rest capacity of the inverter is used for the compensation of power fluctuations of the transmission system during the dark periods. In [22], an 8th order-based power fluctuation damping controller is proposed and in [23], an energy function-based power fluctuation damping controller is proposed for the improvement of power system performance. However, the complexity of the proposed control discussed in [22, 23] gradually increases for larger power system applications. All the discussed damping controllers have used the rest amount inverter capacity in the light period for the fluctuation damping. Therefore, the damping capability of the solar plant is affected during the light period and tends to be zero during the noon period.

As a solution to the above problems, in the proposed manuscript a novel solar-shunt active filter (solar-SHAF) based system is designed for the successful damping of the power fluctuations. The control approach of the proposed solar-SHAF is based on the idea of the novel patent application [24]. During any type of fluctuations/uncertainty, the proposed control approach autonomously stops the solar plant real power generation for a shorter duration (<1 min) and utilizes the total inverter capacity for the damping operation through appropriate reactive power support. When the power fluctuations are well within the acceptable limit, again the solar plant can restore the desired real power in a ramp-wise manner. Moreover, the control approach is also available for activating the damping operation after the successful restoration of solar power by using the inverter capacity. Due to the above condition, the proposed approach prevents the recurrence of power fluctuation and also increases the ramp rate faster than the suggested grid codes [25], where damping condition is not evaluated during the restoration process.

In [19] and [26], similar studies like the regulation of solar plant as a STATCOM mode of operation are studied. In [19], during the dark period, the controller used its full inverter capacity to provide the damping operation but during the light period, the controller used only partial inverter capacity for a similar operation. In [26], the proposed approach is only focused on the voltage control during the dark period (not the light period) in the distribution sector. However, the proposed studies are not emphasizing the power fluctuation damping functions at all. Still, the major drawbacks of [19–26] are (1) it uses the rest inverter capacity after active power generation for the damping operation; (2) the damping performance of the controller is decreased with an increase in active power generation during noon period; (3) none of the above approach also concerns the harmonics.

Therefore, in this study, the novel solar-SHAF concept and the proposed control algorithm are used to control the power fluctuation damping operation by using full inverter capacity for a 24/7 operation basis. The effectiveness of the suggested approach is tested by considering a one-area system (SGIB) [27], a two-area system [28], and a three-area system (12-bus) [29] through a detailed transient analysis.

The total active (P) and reactive power (Q) generation and working condition of the proposed solar-SHAF for 24 h are illustrated in Figure 1. The proposed smart solar-SHAF topology is divided into two sub-sections such as partial solar-SHAF and full solar-SHAF mode.

2 | OPERATION OF SOLAR-SHAF

2.1 | Partial solar-SHAF

In this condition, after fulfilling the required active power generation, the rest solar-SHAF based inverter capacity is used for SHAF operation by compensating the power fluctuations. As indicated in Figure 1, this condition is only active during the light period.

2.2 | Full solar-SHAF

In this condition, the total solar-SHAF based inverter is available for only SHAF operation. At the light period, when the proposed detection unit detects any undesirable low-frequency fluctuations in power output due to any disturbances, the active power flow is disconnected from the power flow. During the disturbance conditions, the proposed approach is operated only in SHAF mode and it provides reactive power support to settle the power fluctuation. After the successful damping of the low-frequency power fluctuation, the active power output of the solar plant is re-established. During that condition, the solar plant increases the active power flow in a ramp-wise manner and restores to its original position without affecting the power flow of the transmission system. In addition to that, the proposed approach also operates in partial solar-SHAF mode.

Figure 2(a) shows the three-phase line representation of a large synchronous generator (SG) attached to an infinite-bus (SGIB) system through a 600 km transmission line [27]. A 100 kW rating of the solar-SHAF model is attached to the
midline bus-2 of the transmission line. Figure 2(b) shows the three-phase line representation of a two-area system with the same rating of solar-SHAF attached to bus-8. In the two-area system, four SGs are attached to the respective buses through a 220 km tie-line [27]. In both single-area and two-area designed systems, the SGs are characterized by their 6th-order model and A-type exciter [27]. In the test system, no power system stabilizer (PSS) is used for the SGs. The detailed constraints for both of the systems are discussed in [27 and 28], respectively. Figure 2(c) shows the single line diagram of a three-area system containing the 12-bus system. The three-area system is generally considered for testing the effect of FACTS approach [29]. To analyze the effect of the suggested FANDR, power flow and harmonic study with the application of the solar-SHAF controller are tested on the three-area system having a different mode of operation.

3 | CONTROL ARCHITECTURE OF THE PROPOSED SOLAR-SHAF

The proposed fault and non-linearity detection unit (FANDU) and complete control architecture of the proposed solar-SHAF are illustrated in Figures 3 and 4. The complete control section is divided into six sub-sections as (1) DC-link inverter voltage regulator (DIVR); (2) traditional solar active power regulator (TSAPR); (3) proposed fault and non-linearity detection controller (FANDR); (4) FANDU; (5) proposed solar active power regulator (PSAPR); (6) harmonic current regulator (HCR); (7) abc – αβ current transformation.

3.1 | DC-link inverter voltage regulator

As illustrated in Figure 4, the regulation of the DC-link voltage plays an important role to generate the appropriate switching signals for the inverter. The overall DIVR is divided into two sections (a) conventional solar-SHAF (CS-SHAF) operation, and (b) SHAF operation [9,10]. In CS-SHAF operational mode, the Perturb and observe (PO) based maximum power algorithm (MPA) technique is used to generate the optimum power ($P^*$) and voltage ($V^*_{dc}$) during day time [30,31]. The actual voltage ($V_s$) and current ($I_s$) of the solar panel is injected to the PO-MPA, to generate the $P^*$ and $V^*_{dc}$. To generate the appropriate active current component ($I_{α ref}$), the $V^*_{dc}$ is compared with the $V_s$ and passed through a PI controller. In SHAF operational mode, the switch ‘S’a position is changed from 1 to 2, and the DC-link voltage is operated at solar panel open-circuit voltage ($V_{oc}$). Due to that the solar panel active power injection is detached from the system [31]. Due to the varying environment and temperature conditions, $V_{oc}$ of the solar panel is continuously changing. For specific reasons, there are huge variations in the $V_{oc}$ observed from various power-voltage and voltage-current characteristics for different solar irradiance and temperature. Therefore, by analysing the above variations in $V_{oc}$, a reference voltage ($V_{dc,ref}$) is selected for the DIVR (set
by the manufacturer). After comparing the computed and reference voltage, the error voltage ($V_{r1}^*$ and $V_{r2}^*$) is passed through a PI controller to generate the $I_{\alpha}^{ref}$ component.

3.2 | Traditional solar active power regulator

The TSAPR regulates the voltage source inverter (VSI) reactive power output in such a way that the solar output power is operated at a unity power factor [32]. This control topology is taken from [30–32] and applied only to normal power system operation where power-factor (pf = 1) is essential for solar system operation. The reactive power (Q) is taken as zero during normal operating conditions. Therefore, the regulator generated $I_{\beta}^{ref}$ is zero. It is guaranteed that during any transient operation the TSAPR is separated from the system control architecture through $S_b$. During the transient condition or any type of power imbalance, the proposed FANDR is taken care of the reactive current ($I_{\beta}^{ref}$) generation.

3.3 | Proposed fault and non-linear detection regulator

The FANDR controller as illustrated in Figure 4, is used to provide reactive power support to the system. FANDR regulates the reactive power output of solar-SHAF, to decrease the low-frequency disturbances that occurred due to fault or transient conditions. In this manuscript, the line current magnitude at the point of common coupling (PCC) of the solar plant is computed as the control signals for the FANDR.

- System-1, $I_F$ indicates the midline current signal where the solar-SHAF is integrated into the system.
Control architecture of the proposed solar-SHAF
System-2, ‘$I_f$’ indicates the midline current between bus-9 and bus-10.

To eliminate the steady-state current component from $I_f$, it is passed through a low pass filter (LPF). The FANDR transfer function ($G_{ff}(t)$) is designed as:

$$G_{ff}(t) = K \frac{1 + \frac{s}{\omega_{	ext{lead}}}}{1 + s \omega_{	ext{lag}}}$$

(1)
where $K$ indicates the regulator gain, $t_{lead}$ is the leading time and $t_{lag}$ is the lagging time. ‘$s$’ is the function name constants of the system during disturbances. The FANDR components such as gain, $up$, and down time coefficients are computed by using an optimization method based on the simplex technique [33, 34]. In the proposed manuscript, the purpose of the controller is to reduce disturbances in the current. The respective objective functions (OF) are computed as:

\[
\text{Objective} = \int_{T_a}^{T_b} (I_F - I_{F}^{ref})^2 dt \quad (2)
\]

where $I_{F}^{ref}$ is denoted as the reference midline current $I_F$, $T_a$ and $T_b$ are the starting and ending time coefficients of the current fluctuations that occurred after the occurrence of the three-phase fault. The main aim of the optimization method is to operate a slave imitation to compute the OF constants in the $n$th run. The obtained OF outcomes are referred to a master system to identify whether the obtained parameters are converging; if not a new set of components are produced for the $(n+1)$th repetition. For the undertaken system-1 and system-2, the OF converges about 52 to 55 times. The detailed operating principle of the FANDR is discussed in [27, 30–33]. The proposed FANDR successfully adds the lead and lag components for improving the system performances by appropriately sensing the oscillating components. The proposed FANDR controller produces the necessary $I_{F}^{ref}$ for solar-SHAF HCR to compensate harmonics and provide appropriate reactive power support during power oscillations.

3.4 Fault and non-linearity detection unit

The FANDU automatically senses the occurrence of undesirable low-frequency power fluctuations/disturbances caused by any grid disturbances like faults. The operation of FANDU is dependent upon the present condition of the proposed system and operates according to the presented flow chart in Figure 3. According to the condition, the proposed FANDU triggers the switches $S_a, S_b,$ and $S_c$ respectively. In this proposed approach, the change in disturbed current component ($\Delta I_F = I_F - I_{F}^{ref} \geq \sigma$) is compared with a pre-set value $\sigma = 5\%$. If the disturbance is exceeding the $\sigma$ value, then the proposed system is operated in solar-SHAF mode for compensating the disturbances and during that period the generation of solar real power is decreased to zero.

3.5 Proposed solar active power regulator

During the full solar-SHAF mode, after the successful damping of the power fluctuations, the PSAPR is used to restore the active power of the solar plant to its pre-fluctuation value ($P_{pre} = 100$ MW) as illustrated in Figure 4. As per the grid code requirement [31, 32], the solar active output power restores the power with a specified ramp rate. Therefore, any power fluctuations and voltage unbalance conditions are easily settled out. In this proposed approach, no additional damping functions are added during the increase in power.

During the partial-SHAF mode, a novel power restoration technique is proposed by which the solar plant continues to provide appropriate power fluctuation damping at the total restoration process. Due to the above approach, the repetition of power fluctuations is cancelled during the entire restoration process. To damp the power fluctuations during the total restoration period, the proposed system has a faster ramp rate.

The PSAPR is operated by using two novel power restoration techniques such as restoration of power in a normal ramped manner and restoration of power in the partial solar-SHAF mode with FANDR as illustrated in Figure 4 and explained below.

3.5.1 Restoration of power in a normal ramped way

In this technique, the regulator shifts the solar active power from zero to 100 MW with a ramp percentage of $K_p$ initializing at time $T = T_\nu$. This is a standard mode of operation recommended for solar active power restoration according to the grid codes [35] and power electronic switch-based inverter standards. In this proposed approach, no damping functions are used for the ramp-up process [35, 36].

3.5.2 Restoration of power in the partial solar-SHAF mode with FANDR

In this technique also, the regulator shifts the solar active power from zero to the pre-fluctuation value by a ramp percentage of $K_p$ initializing at $T = T_\nu$. The solar active power is regulated in the partial solar-SHAF method with FANDR.
FIGURE 7  (a) During normal SGIB voltage and current exchange (200 MW), (b) during increase in voltage and current exchange (430 MW), (c) undertaken system power curve without SHAF.
In this mode of operation, a variation in the proposed technique is also illustrated, according to which the active power is restored from 0 to 100 MW, in a non-linear nature initialization at $T = T_d$ with an exponential time constant $T_c$, as illustrated in Figure 3. $T_c$ is computed by using the decay constant of the power fluctuation mode.

During the active power restoration method, the solar plant operates with FANDR and partial solar-SHAF mode, to provide necessary reactive power support during any transient conditions. The generated inverter and grid output voltages and currents are converted to $abc - \alpha \beta$ voltage and current components through the phased locked loop (PLL). In this proposed approach, the reactive current and voltage component ($\beta$) of the inverter and grid is considered for setting the reactive power limit ($Q^*$). After perfectly restoring the active power demand to its pre-fluctuation value, the reactive power limit is gradually decreased to zero.

3.6 Harmonic current regulator

Figure 4 shows that after generating the reference active ($I_{\alpha ref}$) and reactive current ($I_{\beta ref}$) component from the respective
control strategy, it is further compared with the error in the $\alpha\beta$ current ($I_\alpha^e$ and $I_\beta^e$) component generated from the $\alpha\beta$ inverter current and grid current component ($I_{inv}^e$, $I_{inv}^g$, $I_{inv}^p$, and $I_{net}^p$) as illustrated in Figure 4. The appropriate reference current signals ($I_\alpha^e$ and $I_\beta^e$) are used to generate the pulses for the SHAF operation. To linearize the appropriate current signals and to generate the appropriate control signal ($U_\alpha^e$ and $U_\beta^e$), it is passed through a PI regulator. The appropriate $\alpha\beta$ signals such as $m_\alpha^e$ and $m_\beta^e$ for pulse generation is computed as

$$m_\alpha^e = \frac{V_\alpha^e + U_\alpha^e - \omega I_\beta^e}{V_{dc}/2} \quad (3)$$

$$m_\beta^e = \frac{V_\beta^e + U_\beta^e + \omega I_\alpha^e}{V_{dc}/2} \quad (4)$$

The generated $\alpha\beta$ signals are converted to abc current components for appropriate pulse generation.
The current and voltage components of the inverter and grid are necessary to convert from abc to αβ current component through PLL. From the voltage and current components of the respective inverter and grid, the power factor of the proposed system is computed. The abc-αβ current transformation is needed to separately regulate the active and reactive power demand of the system.

4 | STABILITY ANALYSIS

The above-developed control model stability performance is checked at the three-phase line to ground fault conditions. To check the stability, the Bode, Nyquist, and Step response results
at different control operations like partial and full solar-SHAF with FANDR controller and without filter conditions are obtained and illustrated in Figures 5(a–d) and 6, respectively. Figure 5(a) shows that at 8.77 dB gain margin and phase margin of 44.7°, the proposed partial solar-SHAF with FAND controller provides closed-loop stable responses at the fault condition. The parallel results also obtained from the Nyquist plot as shown in Figure 5(b). Similarly, Figure 5(c) shows that two 180° phase crossings with the corresponding gain margins of −9.35 and 10.6 dB, the proposed full solar-SHAF with FANDR controller provides closed-loop stability. The negative gain margin indicates that the closed-loop stability is lost by decreasing the gain and the positive gain margin indicates that the stability is lost by increasing the gain. This shows the robust stability of the
proposed controller and is also verified through Nyquist plot results as illustrated in Figure 5(d). To obtain a clear idea about the improved stability performance, the respective closed-loop stability response curve of partial and full solar-SHAF with FANDR and without FANDR is illustrated in Figure 6. Figure 6 illustrates that the closed-loop step response exhibits about 20% overshoot during the partial condition and the controller offers a plus/minus 6 dB gain variation to overcome any additional uncertain condition. From Figure 6, it is visualized that without the FANDR controller, the system takes much time around 11.9 s to settle the oscillation. However, by using the proposed partial and full solar-SHAF with FANDR controller, the system offers faster settling as 3.92 and 2.26 s, respectively. The above findings and obtained results justify the need of the proposed controller and show robust stability at any uncertain conditions.

5 | RESULT ANALYSIS

The proposed solar-SHAF based FANDR approach is used to test the performance of system-1 (one-area system), system-2 (two-area system), and system-3 (three-area system). To test the performance, in each and every case a 3\(\varphi\) to ground fault is introduced at SG bus at 2 s for five to six cycles. The simulation results of the undertaken systems and the related case studies are presented below.

Case-1: System-1 (one-area system)

The proposed undertaken system is designed by using an SGIB with 100 MW solar-SHAF attached at bus-2. The undertaken system-1 is tested by using all the possible conditions and presented below.

Condition-1: Power exchange without solar-SHAF regulator

The system-1 is tested without the solar-SHAF regulator. Figure 7(a,b) shows the voltage and current results of the midline bus during normal SGIB operation and an increase in voltage and current exchange rate at bus-2. Figure 7(c) shows the midline and solar active power results. In this condition, the three-phase fault condition is initiated at 2 s. Due to the absence of any controller, the solar power plant output power is reduced from 100 to 0 MW. In this condition, the midline power exchange limit is estimated by initiating a five-six cycle 3\(\varphi\) to ground fault for an undertaken power system and also estimating the settling time of the midline power fluctuations after the clearance of the fault conditions. As per [1–5], the midline power is gradually increased to the desired value till the compensation ratio of the power fluctuation becomes just fewer than the grid acceptance rate of 0–5%. Based on the above concept, it is computed that the SGIB can exchange a maximum of 200 MW power from the SG with 100 MW additional solar active power. During normal SGIB operation the voltage, current, and power waveforms are balanced or settled after a certain time interval. However, the performance for a larger power exchange of about 430 MW is tested for the same fault condition and it shows that the results are quite unacceptable. Therefore, there is a necessity to find an appropriate solution for a larger power system as indicated in Figure 7(a–c).

Condition-2: Power exchange with full solar-SHAF mode and power restoration in normal ramped manner

In this condition, a high rating power exchange (around 430 MW) is considered with the addition of 100 MW of active solar power generation during the mid-day period at maximum solar insolation. The system-1 is tested with full solar-SHAF mode and power restoration in normal operating mode. The respective current and voltage waveforms of the midline system and SG bus are illustrated in Figure 8(a,b). Due to the proposed approach, it is shown that the fluctuations of voltage and current waveforms are settled at a certain time interval. As compared to condition-1, the power is easily exchanged from 200 to 430 MW, respectively. Figure 8(c-1) shows the respective midline power and voltage waveforms of the proposed system-1. Figure 8(c-2) shows that the proposed solar-SHAF using the entire reactive power supports the capability of the inverter to successfully reduce the power fluctuations within 7 s of time. As illustrated in Figure 8(c-3), the PCC voltage is also stabilized at a minimum interval of time. In [36], it is suggested that by using a 10% ramp rate the controller takes around 1 min time to restore the solar power from zero to its original position.

However, in this study, the faster ramp rate is not responsible for the reappearance of any power fluctuation. The ramp rate is computed by using MATLAB/Simulink software as 6 MW/s. After stabilizing the power fluctuation and power flow of the system, the solar power is restored from 0 to 100 MW within a certain interval of 10 s by using the proposed full solar-SHAF mode. It is clearly shown that the restoration period of the power fluctuation is quite faster than the conventional approach.

Generally, FACTS devices such as SVCs [4, 5], STATCOMs [6], Active filters [9, 10] are used to restore the power fluctuations and disturbances of the system-1 by providing dynamic reactive power support. The above FACTS approaches are used to improve the power exchange capability by reducing the power fluctuations. The proposed solar-SHAF transforms the existing solar plant into a SHAF of equal size. Therefore, the solar-SHAF increases the power exchange capability similar to other FACTS devices.

Condition-3: Power exchange with full solar-SHAF mode and power restoration with FANDR in a partial solar-SHAF mode

The proposed full solar-SHAF mode and FANDR with a partial solar-SHAF mode are applied to the similar test system.
as discussed in condition-2. Figure 9(a) illustrates the midline and solar active power results. In addition to that, Figure 8(b,c) shows the reactive-power and PCC voltage results, respectively. Due to the partial solar-SHAF with FANDR mode, the solar active power output results are restored to their original position in a ramp-wise manner. To show appropriate reactive power results, the settling time is marked and mentioned in Figure 8(b). It is justified from Figure 9(a–c) that the novel combined approach restores the power flow to its pre-fault value at only 5 s, instead of using 10 s as indicated in condition-2. In addition to that, the proposed approach also avoids further power fluctuations.

**Condition-4: During the dark period power exchange study with full solar-SHAF FANDR**

Similar to condition-3, the same fault condition is also applied for a 430 MW based SG during the dark period. Figure 10(a) shows the midline power results with FANDR and without FANDR. In addition to that, the solar power figure is also presented. Due to the dark period, solar power becomes zero. Figure 10(b) shows the reactive power output results of the solar-SHAF. Figure 10(a) shows that without using the solar-SHAF based FANDR, the Midline power exchange capability is achieved, but the power fluctuations are not settled which tends to decrease the system performance. From Figure 10(a–c), it is analyzed that due to the proposed solar-SHAF based FANDR, the midline power exchange is significantly improved from 200 to 430 MW during both dark and day time. This test condition shows the feasibility of the proposed approach during the time of power exchange.

**Case-2: System-2 (two-area system)**

The system-2 is designed by using a two-area system with 100 MW solar-SHAF attached at bus-9. The undertaken system-2 is tested by using all the possible conditions and presented below.

**Condition-1: Power exchange without solar-SHAF controller**

In this condition, without using any proposed controller the midline power of the proposed two-area system is exchanged from area-1 to area-2 through line-1 and line-2. A 3Φ to ground fault is introduced at t = 2 s, nearer to the bus-9 line. During that period, the circuit breaker disconnected the disturbed line-2 and fully transfers the power to line-1. Due to the initiation of fault, the midline power of the two-area system is disturbed and takes much time to settle. In addition to that, a solar-SHAF having the capability of 100 MW power generation during day time is connected to the midline of the two-bus. Figure 11 shows the results of the midline power of medium power exchange (230 MW) and high-power exchange (430 MW), and the solar active power output (100 MW) of the proposed two-area system. Figure 11 shows that during the initiation of fault, the solar power of the proposed system drops to zero. In this section, due to the absence of any proposed controller, the possibility of solar output power restoration does not occur. Due to the fault, excess power fluctuation occurred at the midline power flow. It is observed that for high rating power exchange, the power results are more fluctuating in nature.

**Condition-2: Power exchange with full solar-SHAF control mode and power restoration in a normal ramped manner**

In the proposed two-area system as indicated in Figure 2(b), due to the activation of fault fluctuation in power is generally occurred. When the midline power fluctuations are started, the solar output power is decreased to 0 MW and the operation of the solar power plant is changed to full solar-SHAF control mode with FANDR. The proposed solar-SHAF controller uses the total inverter capacity for stabilizing the power fluctuations as well as increasing the rate of power exchange. Figure 12(a) shows the midline and solar active power results. Figure 12(b,c) shows the results of generated reactive power from the solar-SHAF and bus-9 PCC voltage, respectively. Due to the proposed full solar-SHAF model with FANDR, the fluctuations in power are settled to well within the accepted limit by only taking 11 s. The proposed controller also settled the bus-9 voltage rapidly. For safety purposes, the restoration of solar power is started with a 4 s delay of the settlement of midline power. The active solar power value is ramped up to the pre-fault value (100 MW) by taking 12 s-time intervals at a ramp rate of 6 MW/s.

**Condition-3: Power exchange with full solar-SHAF control mode and normal ramped power restoration with FANDR in partial solar-SHAF control mode**

This condition illustrates that power exchange is possible through full solar-SHAF control mode and the restoration of power is possible through partial solar-SHAF based FANDR for a two-area system (similar to the condition-2). Figure 13(a) shows the results of midline power flow and solar active power results. Due to the uses of the proposed approach, the midline power results are settled within 12–13 s and the solar active power restores to its original position by taking only 5–6 s, instead of taking a larger time duration (as presented in condition-2). The combined approach takes very less time to settle the power flow of the solar active power. Figure 13(b) shows the reactive power output results of the two-area system. The proposed solar-SHAF is also capable to supply appropriate reactive power support. Figure 13(c) illustrates the PCC voltage of bus-9. The results indicate that the performance of the proposed approach is 2.5 times faster than the conventional control approach.
Condition-4: Power exchange with full solar-SHAF controller and oscillating power restoration by using partial solar-SHAF mode with FANDR

The performance of the proposed system-2 is studied by using both full solar-SHAF controller and partial solar-SHAF mode with FANDR in an oscillating manner (not in a normal ramped manner). The restoration time constant is computed by using a hit and trial process. The midline and solar power flow results are illustrated in Figure 14. From the above figures, it is justified that the midline power flow takes minimum time to settle down. Due to the partial solar-SHAF based on FANDR in an oscillating manner, the solar power restoration time is reduced to only 2–3 s for achieving the 100 MW rating from 10 s. This test condition is presented just as an initial study by using the proposed controller for a larger system. Regarding this, additional effort is required to methodically compute the time constant of the oscillating ramp-up, for the recent time this is out of the scope of this proposed manuscript.

Condition-5: During the dark period power exchange study with full solar-SHAF FANDR

The proposed two-area system is tested with full solar-SHAF mode during the dark time period. The power results of the proposed two-area system is also applicable for the decreased in power exchange (230 MW) and for the increase in power exchange (430 MW). Figure 15(a) shows that without using the proposed FANDR, the power results are fluctuating in nature. Due to the dark time, the power generation of the solar-SHAF is reduced to zero. During 230 MW power transfer, without using the proposed controller, the system takes some time to settle. During 430 MW power transfer, without using the proposed controller, the midline power is fluctuating in nature for a longer duration. However, by using the proposed FANDR, the undertaken system-2 easily exchanges the power from a lower power rating to higher power ratings as indicated in Figure 15(b). Figure 15(c) shows the generated reactive power results by using the proposed solar-SHAF. Therefore, it is concluded that during the dark time also the proposed controller is working efficiently by providing appropriate reactive power support.

Condition-6: Analysis in between partial solar-SHAF and full solar-SHAF FANDR operational mode

In this condition, the comparison between the partial and full solar-SHAF operational modes is studied in a two-area system for a 70 MW solar power generation (70% of total solar capacity). In partial solar-SHAF mode of operation, the solar-SHAF are not capable to deliver any power fluctuation damping during the peak solar period. The above condition has occurred because the total capacity of the inverter is utilized for the generation of only active power. Therefore, there is no possibility left for regulating the reactive power through the proposed FANDR. For the above reason, in this approach, a full solar-SHAF mode of operation is proposed based on [23] to provide an appropriate power fluctuation damping operation by using full inverter capacity during the day hours. Figure 16 shows the results of midline and solar active power when the restoration of power fluctuation is done by both partial solar-SHAF mode of operation (by using 60% of inverter capacity) and full-SHAF mode of operation (by using 100% of inverter capacity). Figure 16(a) shows that, without changing the active power generation of the solar farm, the proposed inverter takes 23 s to settle the power fluctuation. However, by using full solar-SHAF mode, with the change of the active power flow from 100 MW to zero, the inverter takes 10 s to settle the power fluctuation as indicated in Figure 16(b). The above discussions indicate the superiority of the full solar-SHAF approach over the partial solar-SHAF approach.

Condition-7: Frequency analysis of a two-area system by using FANDR with solar-SHAF mode

In the proposed approach, it is expected that by using FANDR, the system frequency is not affected due to the supply of reactive power support. The proposed solar-SHAF controller is only used to supply the damping operation, which may affect the frequency response of the system. Figure 17(a,b) shows the frequency response of the proposed 430 MW two-area system by using FANDR based solar-SHAF (Similar to condition-3) and without using any FANDR (similar to condition-1). The results are indicating that due to the absence of the controller the frequency results are fluctuating in nature during high rating power exchange. However, the performance of the system is significantly improved by properly adjusting the frequency disturbances. The size of the proposed solar-SHAF based controller is also the same as the conventional power rating solar-SHAF system. Therefore, the frequency of the losses from the proposed solar-SHAF is almost equal to the conventional solar-farm results.

Case-3: System-3 (three-area system)

The proposed undertaken system is designed by using a three-area system (12-bus) with 100 MW solar-SHAF attached at bus-9. The system-3 is tested by using the proposed solar-SHAF based on FANDR and presented below [36, 37]. As per [37], due to the occurrence of the fault in between bus-8 and bus-9, the low-frequency fluctuations occurred at SG-3 and SG-4, respectively. In [37], the fluctuations are settled by using a 100 Mvar Static Var compensator (SVC) at bus-9. In the proposed approach, the same operation of [37] is done by the full solar-SHAF based FANDR. To regulate the SG-3 and SG-4 operation by compensating the fluctuations, the
speed $\omega_3$ and $\omega_4$ are taken as input signals for the proposed FANDR. Figure 18 shows the obtained results for solar-SHAF based FANDR and without FANDR in the three-area system. At $t = 4$ s, the connection between bus-8 and bus-9 is affected due to the occurrence of fault for 4–6 cycles. Figure 16 shows the results of solar farm output, when the fault is detected by the proposed FANDU, the operation of the solar plant changes from the traditional approach to solar-SHAF approach and settles the fluctuations with minimum time. After the settlement of power fluctuations, by taking lesser time the active output power of the solar system restores to its original position (100 MW). By using the conventional approach and without using the FANDR, deviation in the speed of SG-3 and SG-4 is illustrated in Figure 19(a,b). Figure 19(c,d) shows the results of the speed variation of the SG-3 and SG-4, by using the proposed FANDR. From the above results, it is clearly analyzed that by using the proposed approach, the system takes lesser time to settle. In addition to that, the restoration of active power also does not affect the speed performance of the generator.

6 | COMPARATIVE STUDY

From the above test results, it is found that the proposed FANDR based system offers similar results as compared to other FACTS-based system results [4–6, 9, 10]. During normal ramp function, the proposed system in [36] takes around 1 s time to settle the power fluctuation. From the traditional system results proposed in [4, 5, 36, 37], the proposed system offers faster power restoration and excellent generator speed regulation without affecting the active power flow of solar-SHAF.

It is estimated that the proposed control-based system reduces 50 times cost as compared to traditional FACTS-based systems as it uses the existing parameters of the power line. In addition to that, the proposed system also offers additional revenue and power as it facilitates renewable energy sources for power generation. This system is applicable for all system conditions like full solar, partial solar, and dark conditions. For giving a clear quantitative idea, a comparative table is presented and illustrated in Table 1. In this comparative table, all the studied performances are represented according to the settling time of power, frequency, and generator speed restoration time. From the table, it is found that without the controller, the system takes more time to stabilize the power, and for partial and full solar-SHAF with FANDR based system, it takes comparatively lesser time. From the above analysis, it is found that by using the proposed system approach, the system offers significant results as compared to the traditional approach.

7 | CONCLUSION

In this study, a novel FANDR technique based on solar-SHAF is proposed to improve the power exchange capability for larger power lines at fault/transient conditions. FANDR based full solar-SHAF not only enhances the power exchange capability
### TABLE 1 Comparative study

#### 100 MW solar-SHAF attached at bus-2 (one area system) (Fault = 2 s)

| Condition | Without solar-SHAF | Full solar-SHAF mode and power restoration in normal ramped manner | Power flow study | Settling time | Remark |
|-----------|--------------------|------------------------------------------------------------------|-----------------|---------------|--------|
| Power flow study | Midline 200 MW | Midline 430 MW | Solar power 100 MW | ≥ 20 s | Absent |
| Setting time | > 25 s | | | | |

#### Condition-2: Full solar-SHAF mode and power restoration in normal ramped manner

| Power flow study | Midline 200 MW | Midline 430 MW | Solar power 100 MW | Active = 10 s, Reactive = 7 s | | |
| Setting time | NA | 9 s | | | |

#### Condition-3: Full solar-SHAF mode and power restoration with FANDR in partial SHAF mode

| Power flow study | Midline 200 MW | Midline 430 MW | Solar power 100 MW | Active = 5 s, Reactive = 3 s | | |
| Setting time | NA | 10 s | | | |

#### Condition-4: During dark period power exchange with FANDR full solar-SHAF mode

| Power flow study | Midline 200 MW | Midline 430 MW | Solar power 100 MW | | | |
| Setting time | ≥ 12 s | > 25 s | Active = No, Reactive = 5 s | | | |

#### 100 MW solar-SHAF attached at bus-9 (Three Area system) (Fault = 4 s, Duration = 5 to 6 cycle)

| Condition | Without solar-SHAF | Full solar-SHAF mode and power restoration in normal ramped manner | Power flow study | Settling time | Remark |
|-----------|--------------------|------------------------------------------------------------------|-----------------|---------------|--------|
| Power flow study | Midline 200 MW | Midline 430 MW | Solar power 100 MW | | |
| Setting time | ≥ 10 s | > 25 s | | | |

#### Condition-2: Full solar-SHAF mode and power restoration in normal ramped manner

| Power flow study | Midline 200 MW | Midline 430 MW | Solar power 100 MW | | |
| Setting time | NA | 11 s | Active = 12 s, Reactive = 15 s | | |

#### Condition-3: Full solar-SHAF mode and power restoration with FANDR in partial SHAF mode

| Power flow study | Midline 200 MW | Midline 430 MW | Solar power 100 MW | Active = 5 s, Reactive = 10 s | | |
| Setting time | NA | 12–13 s | | | |

#### Condition-4: Full solar-SHAF mode and oscillating power restoration with FANDR in partial SHAF mode

| Power flow study | Midline 200 MW | Midline 430 MW | Solar power 100 MW | | |
| Setting time | NA | 11–12 s | Active = 2–3 s | | |

#### Condition-5: During dark period power exchange with FANDR full solar-SHAF mode

| Power flow study | Midline 200 MW | Midline 430 MW | Solar power 100 MW | | |
| Setting time | Without FANDR ≥ 13 s | Without FANDR > 25 s | | | |

#### Condition-6: Comparison between partial and Full SHAF

| Power flow study | Midline 430 MW for partial SHAF | Midline 430 MW for Full SHAF | Solar power 100 MW | Partial = No active power is used for power oscillation | Full SHAF = Active power is used for power balance (4–5 s) | |
| Setting time | 20 s | 15 s | | | | |

#### Condition-7: Frequency analysis

| Frequency | Without FAND | With FAND | | | |
| Setting time | 8–9 s | 2–3 s | | | |

### 100 MW solar-SHAF attached at bus-8 (two-area system) (Fault = 2 s)

| Condition | Without solar-SHAF | Full solar-SHAF mode and power restoration in normal ramped manner | Power flow study | Settling time | Remark |
|-----------|--------------------|------------------------------------------------------------------|-----------------|---------------|--------|
| Power flow study | Midline 200 MW | Midline 430 MW | Solar power 100 MW | | |
| Setting time | ≥ 10 s | > 25 s | | | |

#### Condition-2: Full solar-SHAF mode and power restoration in normal ramped manner

| Power flow study | Midline 200 MW | Midline 430 MW | Solar power 100 MW | Active = 10 s, Reactive = 7 s | | |
| Setting time | NA | 9 s | | | |

#### Condition-3: Full solar-SHAF mode and power restoration with FANDR in partial SHAF mode

| Power flow study | Midline 200 MW | Midline 430 MW | Solar power 100 MW | Active = 5 s, Reactive = 3 s | | |
| Setting time | NA | 10 s | | | |

#### Condition-4: During dark period power exchange with FANDR full solar-SHAF mode

| Power flow study | Midline 200 MW | Midline 430 MW | Solar power 100 MW | | |
| Setting time | ≥ 12 s | > 25 s | Active = No, Reactive = 5 s | | |

#### Remark

1. Similar operation as compared to FACT devices SVC [4, 5], Statcom [6], active filter [9, 10]
2. Facilitate renewable energy integration
3. Faster settling action compared to without SHAF operation
4. Provide reactive power support during the dark period
5. Applicable for larger power transmission
6. Faster Frequency stability
7. Applicable for complex system and multi-area application
8. Offer better speed regulation of the generator
9. Provide faster action
in the light period but also it can balance the power fluctuations by providing only reactive power support at dark period. During fault conditions, at light period, the proposed approach immediately reduces the active power generation and the total inverter capacity is used to settle the power fluctuation. After balancing the power fluctuation, the solar active power restores to its original position without affecting the system performance. The simulated results of SGIB (one-area system), two-area system, and three-area system (12-bus system) show excellent power restoration process by using full and partial solar-SHAF based FANDR mode, at fault conditions. From the obtained results, it is analyzed that the outcomes are 2.5 to 3 times better than the conventional approach results in terms of damping ratio, speed regulation, and power balance. The suggested solar-SHAF also provides 24/7 operation similar to conventional STATCOM operation. It is also expected that the proposed solar-SHAF based control approach is approximately 50 times lesser than the cost of STATCOM because it utilizes the existing constraints like transformer, substation, filters, protection devices, and relay etc. Not only the proposed approach is used for power fluctuation damping and power restoration, but it is also used to create new revenue by integrating renewable energy in the transmission system and avail 24/7 power supply into the system at a lower cost.

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