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RESEARCH ARTICLE

Tracking and control of power oscillation dampings in transmission lines using PV STATCOM

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Abstract

This paper proposed a new control of PV solar system as a FACTS device STATCOM, called PV-STATCOM, for power oscillation damping (POD) in transmission systems. In this proposed control, as soon as power oscillations due to a system disturbance are detected, the solar farm briefly discontinues its real power generation function and makes its entire inverter capacity available to operate as a STATCOM for POD. As soon as power oscillations are damped, the solar farm restores real power output to its pre-disturbance level while keeping the damping function activated. This results in much faster restoration than that specified in grid codes. During the nighttime, the solar farm performs POD with its entire inverter capacity. The proposed control system provides a significant increase in power transfer capacity on a 24/7 basis in systems that exhibit both local inertial and inter-area oscillatory modes. The developed PV-STATCOM is about 50–100 times cheaper than an equivalent STATCOM for providing POD at the same location. This new control method provides more savings for transmission utilities and opens up a new revenue-making opportunity for solar farms.

Keywords: PV System, Solar System, STATCOM, Power Oscillation Damping, PV STATCOM.

Introduction

Low-frequency electromechanical power oscillations are recognized as one of the major limiting factors in power transfer over long transmission lines. Conventionally, these oscillations are damped by power system stabilizers (PSS) integrated with synchronous generators and static compensators (Arabi *et al.,* 2002). However, flexible AC transmission system devices have been effectively utilized in power systems to dampen these power oscillations and enhance the power transfer capability in transmission lines (Xiao *et al.,* 2003; Mithulanantham *et al.,* 2003). Performances of various FACTS devices equipped with POD controllers are described in the literature, such as Static VAR compensators, Static synchronous compensators, Thyristor controlled series compensators (500 kV), and Convertible static compensators (Haque, 2004; Varma *et al.,* 2009; Simoes *et al.,* 2009). Large-scale PV solar farms over 100 MW are being increasingly connected worldwide. These include Kamuthi (648 MW), in Tamil Nadu, India; Rancho Cielo Solar Farm (600 MW), Solar Star I and II (579 MW), Topaz Solar Farm (550 MW), Agua Caliente Solar Project (295 MW) California Valley Solar Ranch Farm (250 MW) in USA, and Huanghe Hydropower Golmud Solar Park in China (200 MW). The potential for reduction in power system stability with a significant amount of inertia-less power injection from PV solar plants in the grid is described (Sharma, 2011; Tiba & Ricardo, 2012). Smart PV inverter controls such as constant (off-unity) power factor, volt/var, volt/watt, frequency watt, low/high voltage ride through, low/high-frequency ride through, etc., have been proposed and also demonstrated on a large scale PV solar farm (Eftekharnejad *et al.,* 2013). Novel control of PV solar was a farm as STATCOM presented for enhancing the connectivity of wind farms at night and increasing power

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transfer capacity through damping power oscillations both during night and day. This control technique utilized the entire inverter capacity at night and the inverter capacity remaining after real power generation during the daytime for power oscillation damping (Tamimi *et al.,* 2013). An eighth-order POD controller for a large PV solar farm was proposed, whereas an energy function-based design of a POD controller was presented (Morjaria *et al.,* 2014). Both these controllers are relatively complex in design. All the POD controls in the above projects are based on the remaining inverter capacity during the daytime. Hence, the proposed POD capability of the solar farm is limited during the day, indeed becoming zero during hours of full sun. This paper proposed a novel PV-STATCOM control for POD based on a patent-pending technology. In this control, if any disturbance occurs in the power system causing undesirable power oscillations, the PV solar farm autonomously disables its real power-generating function for a short period (typically less than a minute). It makes its entire inverter capacity available for operating as STATCOM to damp power oscillations through reactive power modulation. As soon as the power oscillations are reduced to an acceptable level, the solar farm restores its power output to its pre-disturbance level (Shah *et al.,* 2015; Varma *et al.,* 2015).

Another novel contribution of this project is that the POD function is kept activated during the ramp-up of power to its pre-disturbance value utilizing the inverter capacity remaining after real power generation. This prevents any recurrence of power oscillations and allows a much faster ramp-up than prescribed by grid codes (Bian *et al.,* 2016). where such a damping function during ramp-up is not envisaged. Also, control of PV solar farms as STATCOM has dealt with voltage control only during nighttime (not daytime) on a distribution feeder. This control has been demonstrated during the nighttime with full inverter capacity but during the daytime with only partial inverter capacity. The effectiveness of the proposed PV-STATCOM for POD is demonstrated on a single machine infinite bus (SMIB) system, two-area power system (Arabi *et al.,* 2002), and the 12-bus FACTS power system through detailed electromagnetic transients studies using MATLAB software. The simplex optimization method embedded in MATLAB is utilized to design the POD controller. The small signal residue analysis technique is presented for determining the most effective locations of power system stabilizers (PSS) in power systems (Kundur *et al.,* 1994; Hingorani & Gyugyi, 2000; Mathur & Varma, 2002). The same technique is utilized in this paper to investigate the effectiveness of specific PV-STATCOM locations for POD.

Overview of Photovoltaic Technology

Photovoltaic is the field of technology and research related to devices that directly convert sunlight into electricity using semiconductors that exhibit the photovoltaic effect.

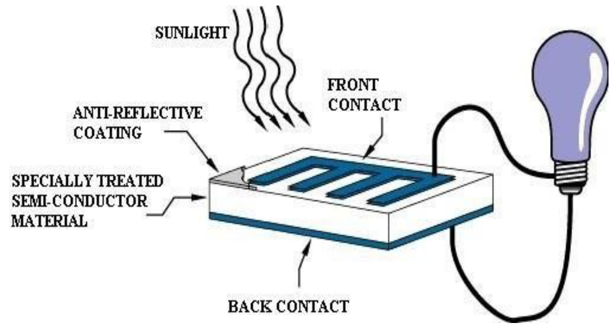

Figure 1: Conversion of light energy to electricity by using solar cell

The photovoltaic effect involves the creation of voltage in a material upon exposure to electromagnetic radiation. The solar cell is the elementary building block of photovoltaic technology. Solar cells are made of semiconductor materials, such as silicon. When photons of light fall on the cell, they transfer their energy to the charge carriers.

The electric field across the junction separates photo-generated positive charge carriers (holes) from their negative counterparts (electrons). In this way, an electrical current is extracted once the circuit is closed on an external load. Figure 1 shows the conversion of light energy to electricity by using a solar cell.

Solar Cell

The photovoltaic action of the selenium differed from its photoconductive action in that the action of light produced a current. No external power supply was needed. In this early photovoltaic device, a rectifying junction had been formed between the semiconductor and the metal contact. Many solar cells electrically connected and mounted in a single support structure or frame are called a 'photovoltaic modules.' Modules are designed to supply electricity at a certain voltage, such as a common 12-volt system. The current produced directly depends on the intensity of light reaching the module. Several modules can be wired together to form an array. Photovoltaic modules and arrays produce direct-current electricity. They can be connected in both series and parallel electrical arrangements to produce any required voltage and current combination. Figure 2 shows the photovoltaic module and array.

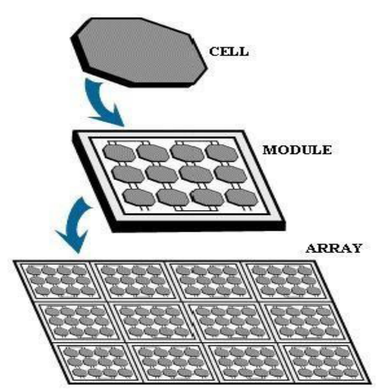

Figure 2: Photovoltaic module and array

Tilt Angle and Orientation

The module's orientation to the sun's direction determines the intensity of the sunlight falling on the module's surface. Two main parameters are defined to describe this. The first is the tilt angle, which is the angle between the plane of the module and the horizontal. The second parameter is the azimuth angle, which is the angle between the plane of the module and the due south. Correction of the direct normal irradiance to that on any surface can be determined using the cosine of the angle between the normal to the sun and the module plane. For higher latitudes, such as those in northern Europe, the maximum output is usually obtained for tilt angles of approximately the latitude angle minus 10–15 degrees.

The proportion of diffuse radiation in the sunlight also affects the optimum tilt angle since diffuse light is only weakly directional. Therefore, for locations with a high proportion of diffuse sunlight, the effect of the tilt angle is reduced. The maximum insulation level is obtained for a south-facing surface at a tilt angle of about 35 degrees, as expected for the latitude of about 51oN. However, the isolation level varies by less than 10% with changing azimuth angle at this tilt angle. A similarly low variation is observed for south-facing surfaces for a variation of +/- 30 degrees from the optimum tilt angle. Figure 3 shows the variation of annual sunlight levels as a function of tilt and azimuth angles.

System Design

There are two main system configurations–stand-alone and grid-connected. As its name implies, the stand-alone PV system operates independently of any other power supply, and it usually supplies electricity to a dedicated load or loads. It may include a storage facility to provide electricity during the night or at times of poor sunlight. Stand-alone systems are also often referred to as autonomous systems since their operation is independent of other power sources. By contrast, the grid-connected PV system operates parallel to the conventional electricity distribution system. It can be used to feed electricity into the grid distribution system or to power loads which can also be fed from the grid. Hybrid systems can be used in both stand-alone and grid-connected applications but are more common in the former because, provided the power supplies have been chosen to be complementary, they allow reduction of the storage requirement without increased loss of load probability. Figure 4 (a), (b), and (c) show the schematic diagrams of the stand-alone, grid-connected, and hybrid systems.

A D-STATCOM consists of a two-level voltage source converter (VSC), a dc energy storage device, and a coupling transformer connected in shunt to the distribution network.

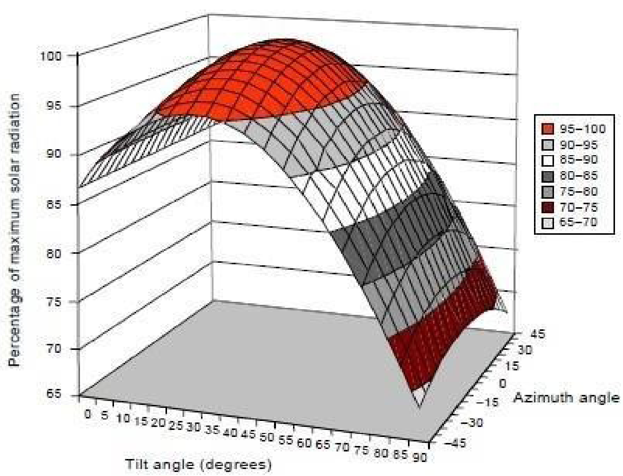

Figure 3: Variation of annual sunlight levels as a function of tilt and azimuth angles.

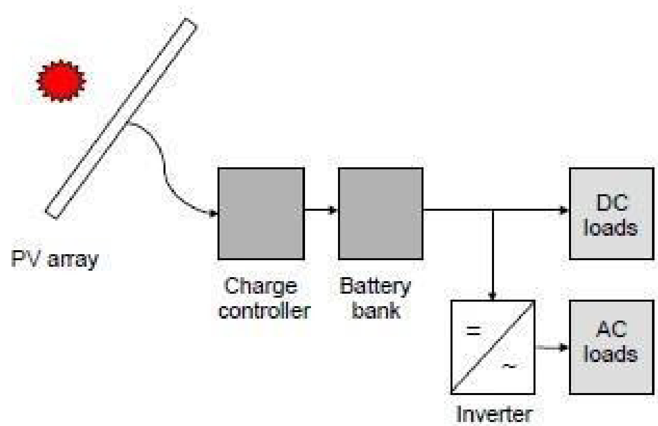

Figure 4: (a) stand-alone PV system

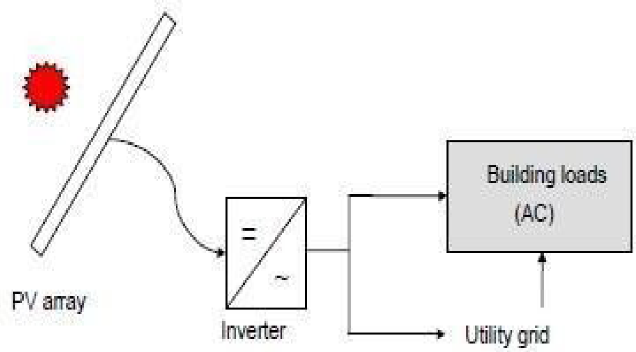

Figure 4: (b) Grid-connected PV system

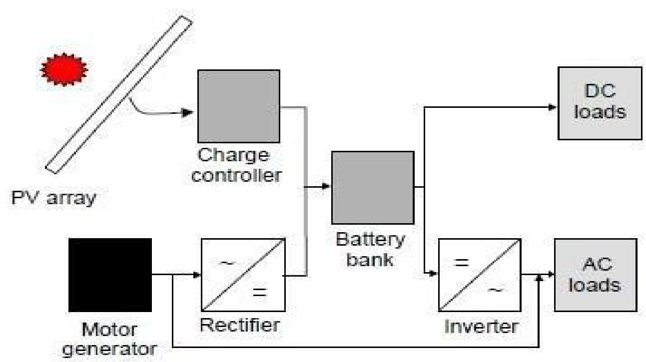

Figure 4: (c) Hybrid system

The VSC converts the dc voltage across the storage device into a set of three-phase ac output voltages. These voltages are in phase and coupled with the ac system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the D-STATCOM output voltages allows effective control of active and reactive power exchanges between the D-STATCOM and the ac system. Such configuration allows the device to absorb or generate controllable active and reactive power.

Static Synchronous Compensator (Statcom)

It may be mentioned that the effectiveness of the D-STATCOM in correcting voltage sag depends on the value of Z_{th} or the fault level of the load bus. When the shunt injected current I_{sh} is kept in quadrature with V_L, the desired voltage correction can be achieved without injecting any active power into the system. On the other hand, when the value of I_{sh} is minimized, the same voltage correction can be achieved with minimum apparent power injection into the system. The control scheme for the D-STATCOM follows the same principle as for DVR. The switching frequency is set at 475 Hz.

Test System

Figure 5 shows the test system used to carry out the various D-STATCOM simulations, and Figure 6 shows the simulation diagram of the D-STATCOM test system.

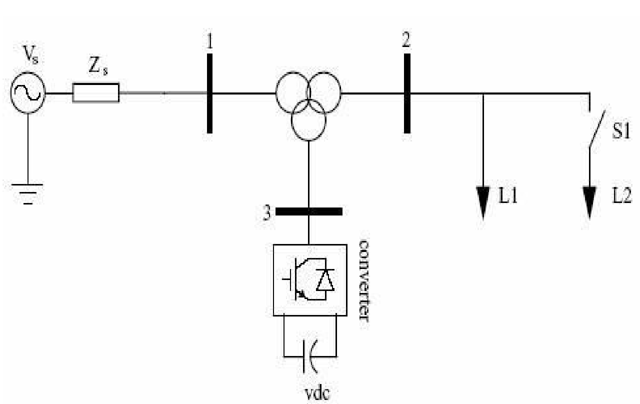

Figure 5: Single-line diagram of the test system for D-STATCOM

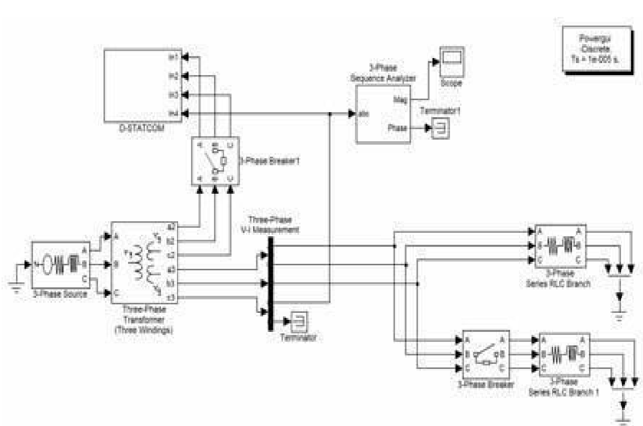

Figure 6: Simulink model of D-STATCOM test system

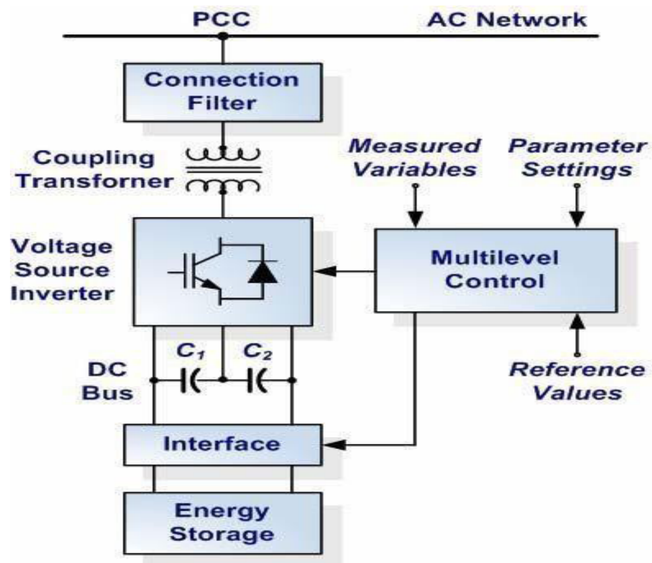

Figure 7: Modeling of the D-STATCOM

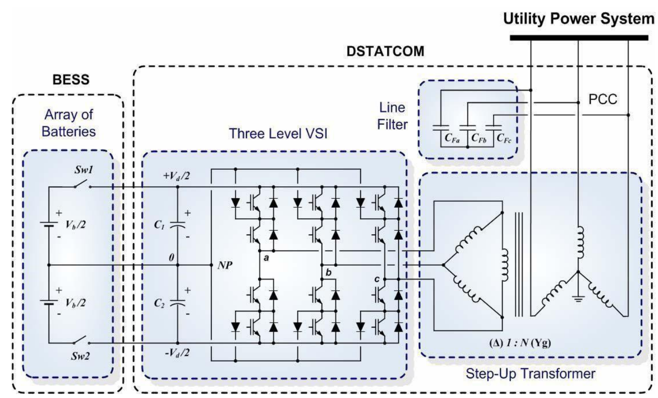

Figure 8: Proposed model of STATCOM/BESS

Modeling of the Dstatcom/Bess

A DSTATCOM consists of a three-phase voltage source inverter shunt connected to the distribution network through a coupling transformer. Its topology allows the device to generate a set of three almost sinusoidal voltages at the fundamental frequency, with controllable amplitude and phase angle. In general, the DSTATCOM can be utilized for providing voltage regulation, power factor correction, harmonics compensation, and load leveling. The addition of energy storage through an appropriate interface to the power custom device leads to a more flexible integrated controller. The ability of the DSTATCOM/BESS to supply effectively extra active power allows for expanding its compensating actions, reduces transmission losses, and enhances the electric grid's operation. Figure 7 shows the modeling of the D-STATCOM.

D-STATCOM includes superconducting magnetic energy storage (SMES), supercapacitors (SC), flywheels, and battery energy storage systems (BESS), among others. However, lead-acid batteries offer a more economical solution for applications at the distribution level that require small devices to supply power intermittently for short periods. Moreover, BESS can be directly added to the dc bus of the inverter, thus avoiding the necessity of an extra coupling interface and thus reducing investment costs. The integrated DSTATCOM/BESS system proposed in Figure 8 is composed of the inverter, the coupling step-up transformer, the line connection filter, the dc bus capacitors, and the array of batteries. Since batteries act as a stiff dc voltage source for the inverter, the use of a conventional voltage source inverter appears as the most cost-effective solution for this application. The output voltage control of the DSTATCOM/BESS can be achieved through pulse width modulation (PWM) by using high-power fast-switched IGBTs.

Proposed System

Figure 9 shows the typical real power output of a PV solar farm P during a sunny day and the remaining reactive power capacity Q during 24 hours. The proposed smart inverter PV-STATCOM has two modes of operation.

Partial PV Statcom Mode

The PV inverter capacity remaining after real power generation is utilized for the STATCOM mode of operation. This mode is available during day time.

Full PV Statcom Mode

The entire PV solar farm inverter capacity is made available for the STATCOM mode of operation.

During the daytime, the real power generation function is discontinued as soon as any unacceptable low-frequency power oscillations due to any system disturbance are detected. The solar inverter is then transformed into a STATCOM, with the entire inverter capacity made available for reactive power modulation. Once the low-frequency oscillations are damped, the real power generation function is reinstated. The solar farm then ramps up its real power output to the pre-disturbance level while continuing to perform POD in the partial PV-STATCOM mode. During the nighttime, the Full-STATCOM mode is available continuously for POD with reactive power modulation utilizing the entire inverter capacity.

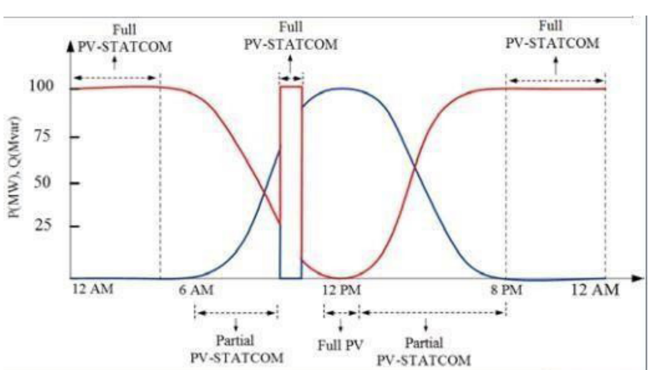

Figure 9: PV Real and Reactive power during 24 hours on a sunny day

Study System Modelling

A] single machine infinite bus (SMIB) system:

Concept of PV-Statcom

Figure 10 illustrates the single-line diagram of the large synchronous generator connected to an infinite bus through a 600 km line. A 100 MW PV solar farm connected at the mid-point of the transmission line. The Two-Area system having four generators connected with the 220 km tie-line is depicted in Figure 11. A 100 MW PV system is connected at the midpoint of the tie-line between buses 7 and 9. In both study systems, the synchronous generators are represented by their detailed sixth-order model and DC1-A-type exciter [1]. No Power System Stabilizer (PSS) is installed on generators. The Two-Area system exhibits local inertial and inter-area modes of oscillations in the power flow.

The 12-bus FACTS power system is widely used for studying the impact of FACTS controls. To demonstrate the effectiveness of the proposed controller, POD studies with PV-STATCOM are performed on the 12-bus FACTS power

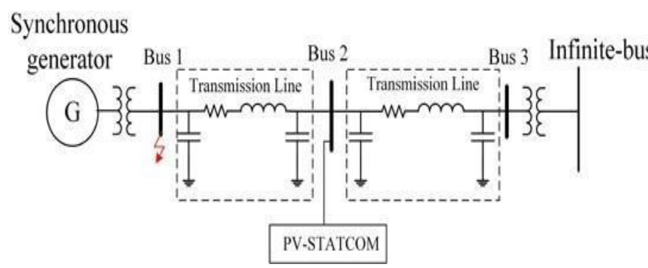

Figure 10: Single-line diagram of a SMIB system with a 100 MW PV plant connected to a midline Two-Area Four Machine System:

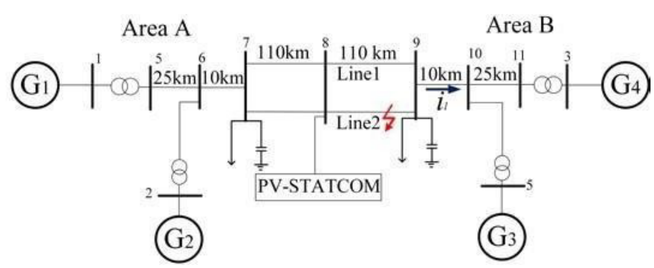

Figure 11: Single-line diagram of a Two-Area system with 100 MW PV plant connected to midline 12 Bus FACTS power system

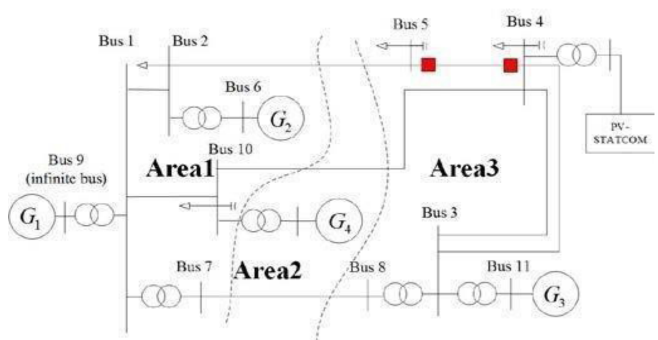

Figure 12: 12 bus FACTS power system with 100 MW PV solar systems at bus 4

system having multiple oscillatory modes. Figure 12 shows the 12-bus FACTS power system with 100 MW PV solar systems at bus 4.

Controllers and Modulation Techniques

A controller is one that compares a controlled variable with a desired one and has a function to correct the deviation produced. The controllers are classified as Proportional, Integral, and Derivative types. The combination of PI and PD is often used in practical systems.

Modulation Techniques

Multilevel inverters generate sinusoidal voltages from discrete voltage levels, and pulse width modulation (PWM) strategies accomplish this task of generating sinusoids of variable voltage and frequency. The most widely used techniques for implementing the pulse with modulation (PWM) strategy for multilevel inverters are Sinusoidal PWM (SPWM) and space vector PWM (SPWM).

Proposed Simulation Model

The proposed system was carried out using MATLAB Simulink block set. Figure 13 shows the simulated block

Table 1: Effects of changing parameters

Parameter	Rise time	Overshoot	Settling Time	Steady state error	Stability
Kp	Decrease	Increase	Small change	Decrease	Worse
Ki	Decrease	Increase	Increase	Significant decrease	Worse
Kd	Min. decrease	Min. decrease	Min. decrease	No change	Better

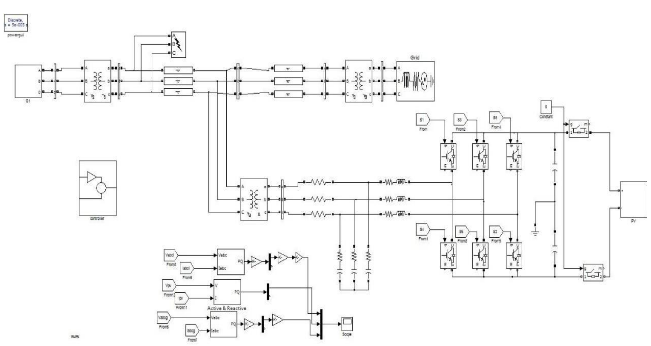

Figure 13: Simulink block diagram of the proposed model

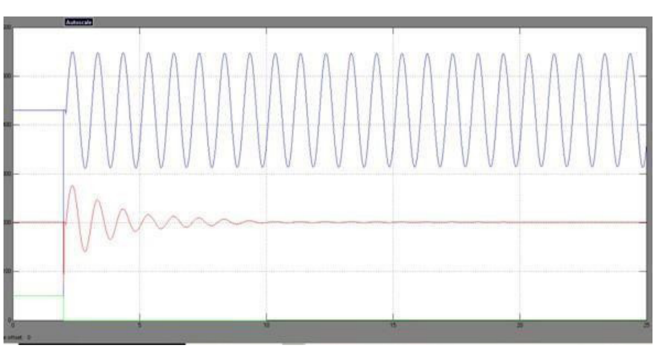

Figure 14: Maximum power transfer capability of the SMIB system

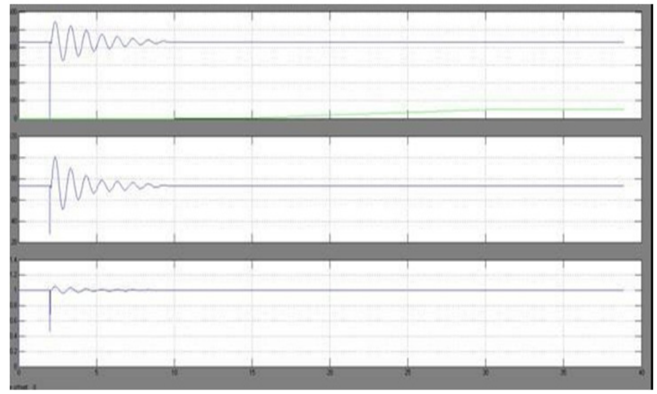

Figure 15: (a) Midline and PV system real powers, (b) PV-STATCOM reactive power, (c) Midline voltage during POD and normal ramped power restoration

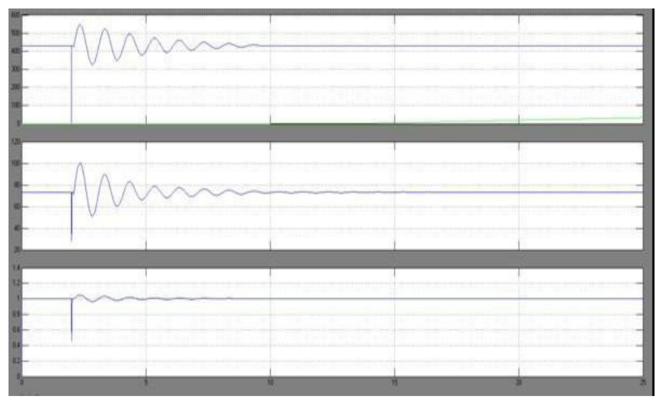

Figure 16: (a) Midline and PV system real power, (b) PV-STATCOM reactive power, (c) Midline voltage during POD and power restoration in Partial PVSTATCOM damping mode.

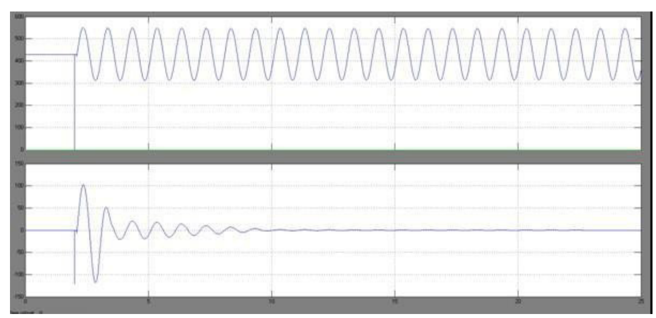

Figure 17: Nighttime (a) Midline real power without POD with PV STATCOM control, (b) PV- STATCOM reactive power during POD

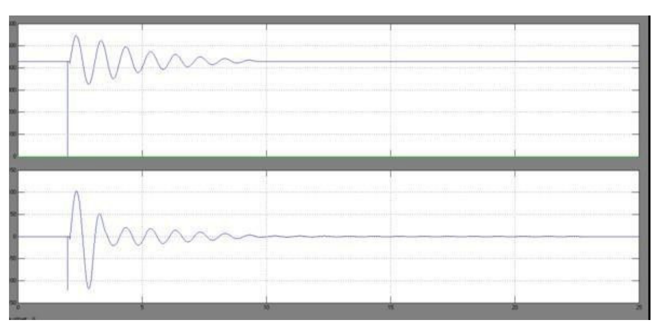

Figure 18: Nighttime (a) Midline real power with POD with PVSTATCOM control, (b) PV- STATCOM reactive power during POD

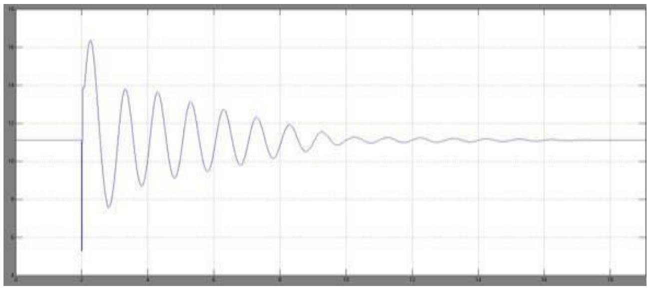

Figure 19: Nighttime using the fuzzy logic controller (a) Midline real power without POD with PV-STATCOM control, (b) Midline real power with Full PV-STATCOM POD Control, (c) PVSTATCOM reactive power

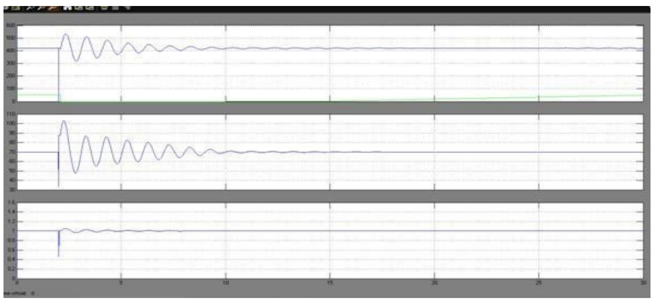

Figure 20: (a) Midline and PV real power, (b) PV reactive power, (c) Midline voltage during POD and power restoration

diagram of the proposed model. Figure 14 shows the maximum power transfer capability of the SMIB system. Figure 15 (a), (b), and (c) shows the midline PV system real powers, PV-STATCOM reactive power, and Midline voltage during POD and normal ramped power restoration. Figure 16 (a), (b), and (c) shows the midline and PV system real power, PV-STATCOM reactive power, and midline voltage during POD and power restoration in Partial PVSTATCOM damping mode. The same 5-cycle fault at t = 2 sec is initiated for a generator power output of 430 MW at nighttime. Figure 17 (a) portrays the behavior of 430 MW power flow in the tie line with and without the PV-STATCOM POD control. Figure 18 (a) and (b) show the Night time midline real power without POD with PVSTATCOM control and PV- STATCOM reactive power during POD. The solar farm with the proposed Full PV-STATCOM POD control successfully enables the same increase in power transfer from 200 MW to 430 MW in the nighttime as in the daytime. Figure 19 (a), (b), and (c) shows the nighttime using fuzzy logic controller midline real power without POD with PV-STATCOM control, midline real power with Full PV-STATCOM POD Control, and PVSTATCOM reactive power. Figure 20(a), (b), and (c) shows the midline and PV real power, PV reactive power, and midline voltage during POD and power restoration.

Conclusion

This paper proposed a new control of transmission lines connected to large PV solar systems as a STATCOM for damping power oscillations and thereby substantially increasing the power transfer capacity of the network. The proposed control provides POD through reactive power modulation utilizing the entire inverter capacity during nighttime. During the daytime, the solar farm discontinues its real power generation function briefly (about 15 sec) and utilizes its entire inverter capacity for POD. It subsequently gradually restores power generation to its pre-disturbance level while keeping the POD function activated by utilizing the remaining inverter capacity. EMTDC/PSCAD simulation studies demonstrate the effectiveness of the proposed PV-STATCOM control in a single machine infinite bus (SMIB) system, which exhibits local inertial oscillatory mode, a two-area system that displays both local inertial and inter-area modes of oscillations, and the 12 bus FACTS power system which has multiple inter-area modes of oscillations. In the SMIB system, a 100 MW midline connected PV solar system increases the power transfer capacity by 230 MW. In contrast, in the Two-Area system, a 100 MW PV solar system increases the power transmission limit by 200 MW. Moreover, the proposed power restoration technique for keeping POD activated is more than 3 times faster than that specified by grid codes. The proposed circuits were developed and implemented using MATLAB Simulink block set, and the simulation results were found satisfactory.

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