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SSR Mitigation Using PV Solar STATCOM

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Abstract:
This paper presents a peculiar control of a large scale PV solar farm as STATCOM which is said to be PV-STATCOM, for palliation of sub synchronous resonance (SSR) in a steam turbine driven synchronous generator connected to a series compensated in the transmission line. During dusk, the PV solar farm can operate as a STATCOM with its entire inverter capacity for SSR mitigation. During sunshine, if a system fault triggers SSR, the solar farm autonomously discontinues its normal active power generation and releases its entire inverter capacity to operate as PV-STATCOM for SSR avoidance. Once the sub synchronous resonances are damped, the solar farm returns to its normal real power production. Electromagnetic transients studies using EMTDC/PSCAD are performed to demonstrate that a solar farm connected at the terminals of synchronous generator in the IEEE First SSR Benchmark system can damp all the four torsional modes at all the four critical levels of series compensation, and return to normal PV power production in less than half a minute. This proposed PV-STATCOM technology can either obviate or reduce the need of an expensive FACTS device to accomplish the same objective. Furthermore, this technology is more than an order of magnitude cheaper than a conventional SVC or STATCOM of similar size.

Index Terms: PV solar system, Sub Synchronous Resonance (SSR), series compensation, FACTS, STATCOM, PV-STATCOM, solar energy, smart inverter, power ramping.

I. INTRODUCTION

Series capacitive compensation is an effective means for increasing the power transfer capacity of transmission lines. However, the potential of subsynchronous resonance (SSR) in such lines must be examined apriori and adequately addressed [1]-[3]. SSR is an unstable electrical power system condition that can manifest as steady state induction generator effect, torsional interaction or as transient torque amplification [2]-[3]. SSR resulted in damage to generator shaft in the steam turbine driven synchronous generator in Mohave plant, Nevada, USA, in 1970 and 1971 [1]. SSR was reported due to adverse interaction between HVDC converter controls and generator torsional system at Square Butte, North Dakota, USA, in 1980 [4], [5]. Damaging over voltages due to subsynchronous interactions between Type 3 wind farms andseries compensated lines have also occurred in Texas [6], [7]. Several countermeasures have been investigated and utilized to alleviate subsynchronous resonance (SSR) since its first occurrence, including various filters, excitation system control and protection systems [8]. Flexible AC Transmission System (FACTS) devices are known to be effective solutions for preventing SSR [9]-[24]. The concept of damping SSR in turbine driven synchronous generators through reactive power modulation by shunt connected dynamic reactive power compensators is presented in [8], [11]-[15], and actually implemented in [16]. The concept has been further demonstrated for SSR mitigation by Static Var Compensators (SVC) in [13], [15] and by STATCOMs in [17], [18] in addition to several other publications. The essential concept is as follows. Reactive power from the dynamic reactive power compensator is modulated in response to the turbine generator rotor oscillations causing a corresponding voltage modulation at the interconnecting bus. This modulation is performed in such a manner that subynchronous currents are made to flow into the armature of the turbine generator. These subsynchronous currents are in phase opposition and tend to cancel the original SSR causing subsynchronous currents caused by the interaction between series capacitors and transmission network inductance. A Static Var Compensator (SVC) connected at the terminal of the synchronous generator and utilizing a generator speed based damping controller was shown to successfully damp SSR for all the critical series compensation levels [13], [15]. A generator bus connected STATCOM employing rotor speed based auxiliary controller could successfully damp SSR [17]. A nonlinear optimization based design of a subsynchronous damping controller for STATCOM utilizing locally available STATCOM bus voltage and reactive current signals was proposed in [18] to suppress SSR in a system adapted from the IEEE First SSR Benchmark System [25]. SSR alleviation has also been proposed using other FACTS devices e.g., Thyristor Controlled Series Compensator [19], Static Synchronous Series Compensator SSSC [20-22] and Superconducting Magnetic Energy Storage System (SMES) [23]. PV solar power systems are being increasingly employed worldwide to fulfil energy needs. Several large-scale PV solar farms of rating in excess of 100 MW are operational and more are being planned. Most of these solar systems are connected to transmission systems. Some of the large PV solar farms are: Longyangxia Dam Solar Park (850 MW) in China, Solar Star I and and II (579 MW) in USA, Topaz Solar Farm and Desert Sunlight Solar Farm (550 MW each) in California, USA; Huanghe Hydropower Golmud Solar Park (500 MW) in China, Charanka Solar Park (345 MW) in India, Agua Caliente Solar Project (295 MW) in Arizona, USA; California Valley Solar Ranch (250 MW) in California, USA [26]-[29]. It is important to note that the Agua Caliente Solar Project (290 MW) constructed by First Solar is connected to Hassayampa-North Gila 500 kV transmission line that is series compensated [29]. A new concept of using PV solar farms as a STATCOM was proposed in 2009 [30], [31]. This concept termed PV-STATCOM utilized the entire capacity of PV inverter during nighttime and the inverter capacity remaining after real power production during daytime for performing various grid support functions, such as voltage regulation [30], increasing the connectivity of neighboring wind farms [32], and enhancing the power transmission capacity by damping power oscillations [33]. A limitation of this concept was that it could not be applied during noon time or hours when the solar farm was producing its rated power output. A new patent pending technology [34] is used in this paper to propose a comprehensive PV -STATCOM control whereby, a solar farm can function as a full STATCOM both during night and anytime during the day, for mitigating SSR. Electromagnetic transient studies using EMTDC/PSCAD are conducted to demonstrate that a PV solar farm connected at the generator terminals with the proposed PV-STATCOM control successfully mitigates SSR for all the critical levels of series compensation in a study system adapted from the IEEE First SSR Benchmark System [25]. This is for the first time to the best of authors' knowledge that a PV solar farm control is being proposed for preventing SSR

II. CONCEPT OF PV-STATCOM

Fig.1 depicts the typical pattern of the PV solar farm power generation on a sunny day and the remaining reactive power capacity over a 24-hour period. Two modes of PV-STATCOM operation are illustrated in Fig. 1: *Partial PV-STATCOM mode*: In this mode, the real power generation continues unabated based on available solar radiation. The inverter capacity left after real power generation is used for STATCOM operation. This mode is used during daytime typically during early morning and late afternoon [33].

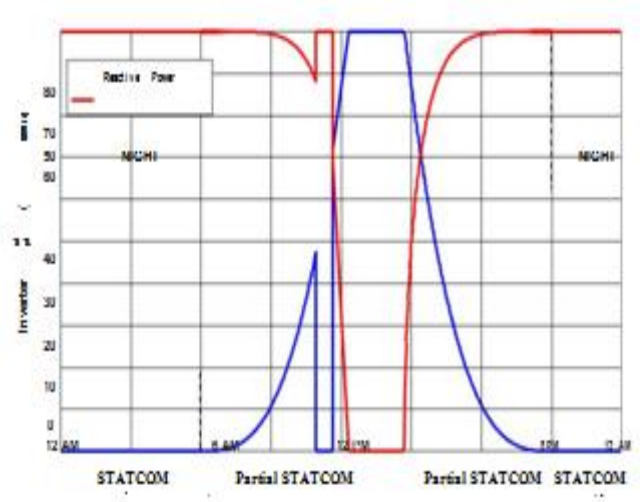

Figure.1. Power output of a PV solar farm for 24 hours duration

III. STUDY SYSTEM

Fig. 2 illustrates the study system in which the IEEE First SSR benchmark system [25] is augmented with a PV solar farm at generator bus. The mechanical system is modeled fully by its six mass-spring system: the high pressure turbine (HP), the intermediate pressure turbine (IP), the low pressure turbines (LPA and LPB), the Generator (GEN), and the exciter (EXC) . The mechanical damping is considered zero in all modes to represent the worst damping condition [15]. This radial system produces subsynchronous resonances with four torsional modes: 15.71 Hz (Mode 1), 20.21 Hz (Mode 2), 25.55 Hz (Mode 3), and 32.28 Hz (Mode 4). The synchronous generator and the entire network are modeled in EMTDC/PSCAD software according to parameters provided in [25]. No AVR is considered on the synchronous generator [25]. The synchronous generator although rated at 892.4 MVA [25] is operated at 500 MW. However, a 300 MVA PV solar inverter is connected at generator bus to make the total power generation at the generating end match with that in [25]. The series capacitive reactance (X_C) of the system is changed to excite the different torsional modes. The values of X_C (p.u.) for which different torsional modes have their largest destabilization are as follows: Mode 1 (0.47 p.u.), Mode 2 (0.38 p.u.), Mode 3 (0.285 p.u.), and Mode 4 (0.185 p.u.) [15]. The PV solar system is modeled with an equivalent voltage source inverter (VSI) comprising six insulated gate bipolar transistor (IGBT) switches, and a dc current source which follows the I-V characteristics of PV panels of the PV solar farm system [33], [35]. With the utilization of a maximum power point tracking (MPPT) algorithm, the PV solar farm operates at its maximum power point in normal operation [36-37]. A large dc capacitor is employed to hold the dc voltage approximately constant at the dc side of the inverter [38].

IV. INVERTER CONTROL SYSTEM

STATCOM is a shunt connected VSI with the ability to dynamically control reactive power with a rapid response time (typically, 1-2 cycles) [9]. The proposed control of the PV solar farm as PV-STATCOM is illustrated in Fig. 2. It is known that a STATCOM with voltage control alone is unable to damp the torsional SSR oscillations and hence an auxiliary damping controller is required [10],[13],[15],[17]. The DC voltage controller block including the Maximum Power Point Tracking (MPPT) subsystem adjusts the dc side voltage of inverter to the desired value. The PV inverter control is based on the *dq*-reference frame model of VSI [33], [36-37]. The phase-locked loop (PLL) block is utilized to estimate the angle of the grid voltage [37]. The voltage vector for *dq*-frame modeling is aligned with the quadrature axis, and therefore V_d equals zero. Thus the reactive and active powers of VSI are controlled through the *d*-axis and *q*-axis loops, respectively. The damping controller block utilizes the generator speed signal to produce the *d*-axis reference current $i_{d\text{-}ref}$ for current controller. By employing the dc side voltage and current, the DC Voltage controller block provides the *q*-axis reference current $i_{q\text{-}ref}$. The current control block subsequently controls the output current of the inverter, as described below.

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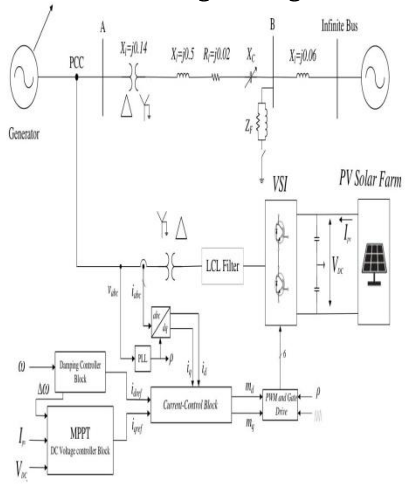
The main Circuit diagram is given below:



CURRENT CONTROLLER

The current-control loop as an inner loop is shown in Fig. 3. The function of the current-control loop is to regulate the acside current of VSI by using sinusoidal pulse width modulation (SPWM) strategy [36]. According to Fig. 2, the i_d and i_q (d-axis and q-axis component of ac side current, respectively) are first compared with their reference values i_{d-ref} and i_{q-ref}. The error signals are then processed by proportional integral (PI) controllers, and their corresponding outputs are augmented with the decoupled feed forward signals [37]. The PI controller parameters are tuned by a systematic hit-and-trial method to achieve the fastest step response, least settling time, and an overshoot less than 10% [33]. A decoupled feed forward technique is utilized to decouple dynamics of d-axis and q-axes, and improve the disturbance rejection ability of the closed-loop system [37]. The resulting signals are normalized to produce the modulating indices m_d and m_q, where, m_d and m_q respectively, represent the d-axis and q-axis components of the three-phase PWM modulating signal (m_{abc}). Finally, m_d and m_q are converted to m_{abc} and compared with a high-frequency triangular wave to generate the proper IGBT switching signals. An LCL filter attenuates the VSI ac side switching ripple, and provides current and voltage with low distortion for the system through a coupling transformer [40], shown in Fig. 2

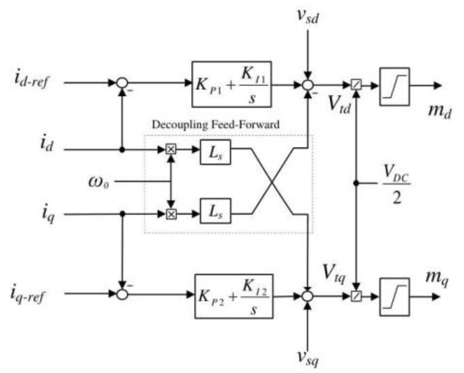


Figure.2. Current-Control block diagram

DAMPING CONTROLLER

Fig. 3 illustrates the configuration of the proposed SSR damping controller of the PV-STATCOM. Since it is intended to utilize the entire STATCOM inverter capacity only for damping SSR, the voltage controller typically employed in the STATCOM is not implemented. The damping controller utilizes generator speed signal for damping SSR. The PV-STATCOM is connected at the terminals of the turbine driven synchronous generator. It is therefore expected that the generator rotor speed signal will become available to the PV-STATCOM control without any appreciable delay. This is the approach adopted by almost all the papers dealing with SSR mitigation by Flexible AC Transmission System (FACTS) devices connected at the terminals of the turbine generators [13], [15-17], [23-24]. Hence, the same approach has also been adopted in this paper. The generator speed is continuously measured and passed through the washout block to obtain the generator speed deviation which reflects the SSR occurring in the generator. It is enhanced by a gain factor K and phase shifted by 180^o to produce the d -axis reference i_{d-ref} for the current loop controller. This controller produces i_{d-ref} in a manner that the corresponding PV-STATCOM reactive power exchange can damp the subsynchronous resonances. The best controller parameters are obtained through a systematic hit-and-trial method to result in a minimal settling time and acceptable over shoot (less than 10%) in generator speed [31]. There are analytical approaches to design the damping controllers by FACTS devices such as [17], [18], [21], [41] and [42], which are more efficient than gain selection through trial and error. However, as the objective of this paper is to demonstrate a new concept of SSR mitigation by PV solar farms control as STATCOM (PV -STATCOM), a simpler controller parameter selection through systematic trial-and -error method was chosen.

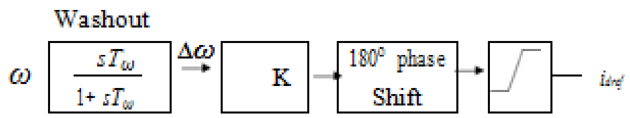


Figure. 3. Damping Controller Configuration

DC VOLTAGE CONTROLLER

It is comprised of the MPPT block, and a PI controller. The MPPT block is simulated in EMTDC/PSCAD software based on an incremental conductance algorithm [43]. The MPPT block produces V_{dc-ref} to control the active power generated by PV solar farm. The measured dc voltage is compared with V_{dc-ref} to create an error signal. The PI controller processes this error signal and generates the q-axis reference i_{q-ref} for the current loop controller. The PI controller parameters are tuned by a systematic hit-and-trial method in the same manner as the PI controller of the current-loop controller. The flow chart of the proposed DC voltage controller for PV-STATCOM operation is portrayed in Fig. 5(b). The DC voltage controller constantly monitors if the system is operating in a healthy manner and no SSR are initiated i.e., the rotor speed deviation Δω is less than a pre-specified quantity which is chosen to be 1 rad/sec. In this case, the Full PV-STATCOM mode is not activated and the system operates in normal PV power generation mode with V_{dc-ref} set to V_{MP}, the maximum power point voltage. If SSR are caused due to any system disturbance or fault, and the rotor speed deviation Δω exceeds 1 rad/sec, the Full PV-STATCOM mode is initiated. This is accomplished by setting V_{dc-ref} to V_{oc} which is the open circuit voltage of the solar panels. The active power generated by the solar panels is made to go to zero and the entire inverter capacity is released for STATCOM operation to damp SSR.Once the SSR are mitigated, i.e., Δω<1 rad/s, the DC voltage controller gradually resumes normal solar power generation by decreasing the dc voltage to its pre-fault value V_{MP} in a ramped manner [44-46]. Simultaneously, the partial PV-STATCOM mode is enabled. In this mode while the real power generation is being ramped up, damping of SSR is continued with the inverter capacity remaining after real power generation. This ramp-up of power with SSR damping control in operation is another novel contribution of this paper which has not been reported earlier. Once V_{dc} becomes equal to V_{MP}, the partial PV-STATCOM operation is disabled and Full PV power generation is resumed.

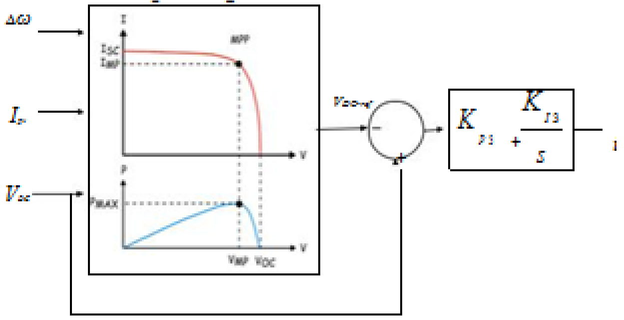
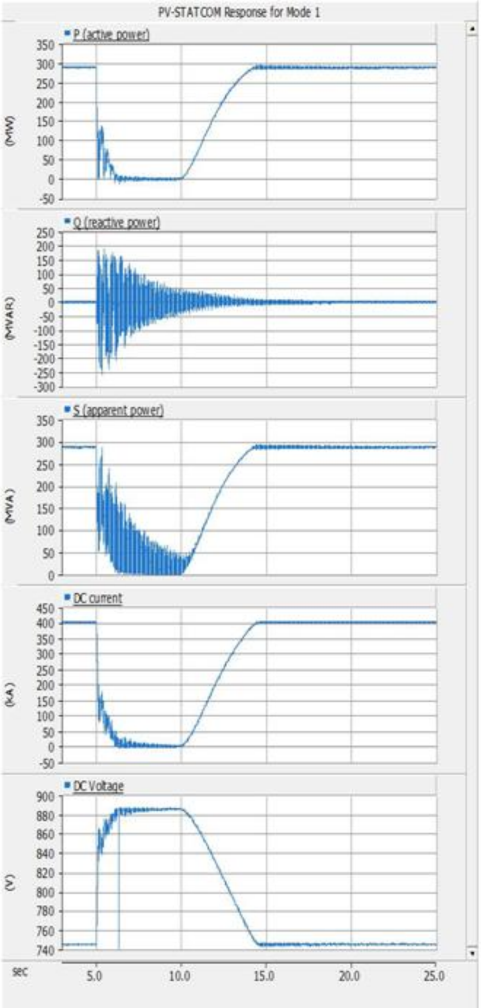
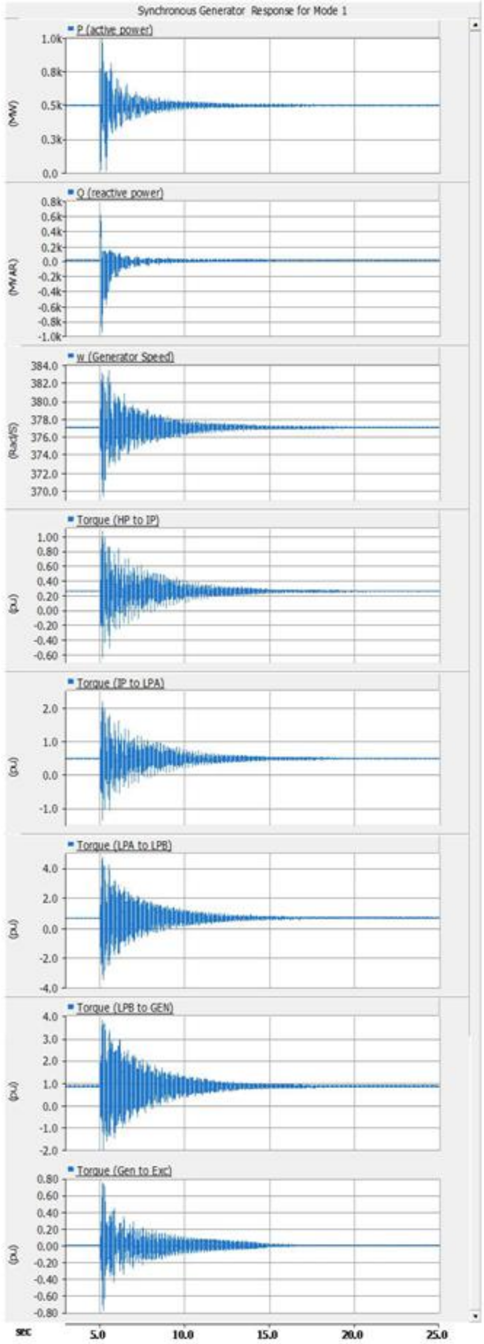


Figure.4. DC voltage controller

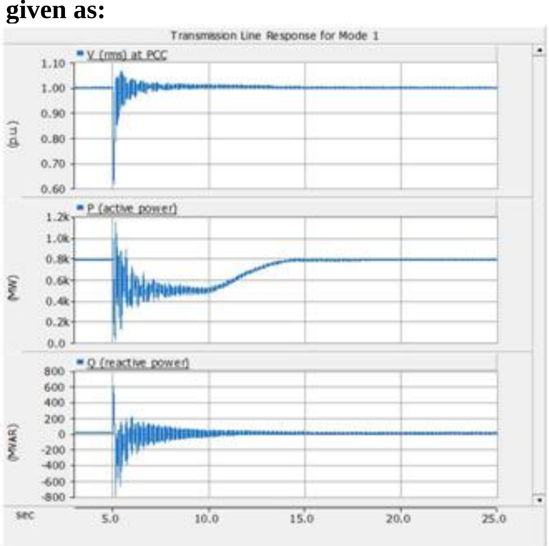
ELECTROMAGNETIC TRANSIENTS STUDY OF SSR DAMPING: Studies for damping subsynchronous resonances using PV-STATCOM control are now performed using EMTDC/PSCAD software. These studies are reported for the most stringent case when both the synchronous generator and the PV solar system are producing their rated power representing a similar power flow as [25]. A three-line-to-ground (3LG) fault for five cycles is initiated at bus B at *t=5 sec*. These fault studies are performed for four critical levels of series compensation when the four respective torsional oscillatory modes are most undamped, as described in [15], Due to space considerations, the detailed responses are reported only for the damping of Modes 1 and 4, which are more destabilized as compared to Modes 2 and 3. This shows the PV-STATCOM response for damping of Mode 1 SSR.



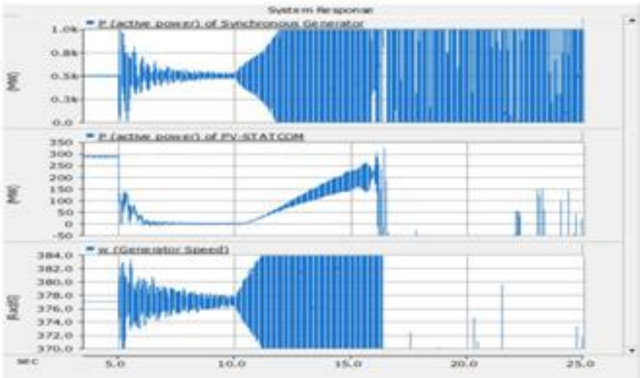
Synchronous generator response for damping of Mode 1 SSR is given below:



Transmission system response for damping of Mode 1 SSR is given as:



The grid codes further specify a range for the rate at which the power may be ramped up depending upon system characteristics. A typical specification is that the increase in active power supplied to the network by the power source must not exceed a maximum gradient of 10% of the agreed active connection power per minute [46]. The appropriate ramp-rate for a specific system may be determined from off-line system studies. This paper has proposed a novel fast method of reconnection of PV solar farm while keeping the PV-STATCOM SSR damping function activated. It is demonstrated from Figs. 7-9 that with this proposed technique the active power can be ramped up from zero to 300 MW in about 5 seconds without resumption of SSR. To demonstrate the effectiveness of this proposed technique a new study is performed. In this study, after SSR has been mitigated and the generator rotor speed has stabilized to within acceptable limits at *t* = 10 sec in Figs 7-8, the power ramping up is performed without the PV-STATCOM damping function. The ramp-up rate is slowed down three times, i.e. the power is ramped up from zero to 300 MW over 15 sec instead of 5 sec as in Figs with PV-STATCOM damping control in operation. Fig. 10 portrays the response of real power of the synchronous generator, the active power of solar farm, and generator rotor speed. The system is seen to become unstable due to recurrence of SSR. This clearly shows the efficacy of the proposed ramp up with PV-STATCOM damping control active. System response for Mode 1 SSR without damping controller during ramp up is given as:



Rapidly emerging, large utility scale PV solar farms are likely to find themselves being connected in transmission systems that are series compensated. This paper presents a novel patent-pending concept of autonomously controlling such large utility scale PV solar farms as STATCOM, termed PV-STATCOM, for mitigating subsynchronous resonance (SSR) in steam turbine driven synchronous generators connected to series compensated transmission lines. The proposed PV-STATCOM control provides solar farm the capability to mitigate SSR both in the night and anytime during the day. In the night, since the solar farm is idle, the entire inverter capacity is utilized for PV-STATCOM operation. During the day, at any time, if SSR is triggered due to any system disturbance, the solar farm autonomousl discontinues its normal real power generation function and transforms into a STATCOM with the full inverter capacity for SSR mitigation. Once the subsynchronous resonances are reduced below an acceptable level, the solar farm autonomously returns to its prefault real power generation level in a ramped manner. Studies are conducted on the IEEE First SSR Benchmark system [25] having a large 300 MVA solar farm connected at the generator terminals producing its rated power, to simulate similar study conditions as in [25]. The PV-STATCOM SSR damping control utilizing generator rotor speed as the control signal is developed in *d-q* frame of reference. PSCAD/ EMTDC based electromagnetic transients simulation studies are conducted for all the four critical levels of series compensation [25]. The following conclusions are drawn:

1) The PV-STATCOM successfully mitigates all the four torsional modes at all the four critical levels of series compensation.

2) The total time taken by the PV-STATCOM from the autonomous initiation of damping control to mitigate the different subsynchronous mode oscillations and return to pre-fault normal solar power production is: 9.68 sec for Mode 1, 7.96 sec for Mode 2, 6.81 sec for Mode 3 and 6.77 sec for Mode 4, oscillations respectively.

This time of interruption of PV solar power generation is comparable to a cloud passing event.

3) The PV-STATCOM reactive power required to damp SSR for all the critical series compensation levels in this study is less than 200 Mvar.

4) The novel concept of ramping up keeping the SSR damping function of PV-STATCOM activated allows a ramp-up rate much faster than that specified in grid codes without resurgence of SSR. The studies demonstrate that the proposed PV-STATCOM control on large utility scale PV solar farms can successfully mitigate potentially dangerous subsynch ronous resonances in synchronous generators connected to series compensated lines. The PV-STATCOM control can potentially obviate the need for installation of an expensive SVC or STATCOM connected to the generator terminals for the same purpose. Under the current power market situation, the owner of synchronous generator normally may not want to share such confidential information about rotor oscillations to other generation owner such as the PV solar farm which is a competitor in the market. However, this paper proposes a new concept by which the PV solar farm can provide SSR mitigation for the synchronous generator in a highly cost effective manner as compared to the installation of a FACTS device exclusively for the purpose of SSR alleviation, assuming both are connected close to the terminals of the synchronous generator. In the proposed concept, the solar farm is not acting as a competitor to the synchronous generator. Instead it is providing a very valuable service in form of protection against shaft damages in the synchronous generator due to SSR. The synchronous generator will therefore not be averse to sharing its rotor oscillation information with the PV solar farm. It is expected and also proposed that appropriate agreements among the synchronous generator owner, concerned utility, system operator, solar farm owner and the inverter manufacturer may be made to implement such a cost-effective solution. The grid codes are presently being revised to accommodate smart inverter functions. It is recommended that this smart SSR alleviation function with PV solar farms controlled as PV-STATCOM be incorporated in the emerging grid codes. Mechanisms should also be evolved for compensating the PV solar farms financially for this very important service of SSR mitigation.

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