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Investigating the effect of Virtual Synchronous Machine in Power system on Low Frequency Oscillations

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Abstract—*Power system is going through a paradigm change from centralized generation to distributed generation and further on to smart grids. DGs are often connected to a grid by power inverters. The inverters used in DGs are generally controlled by phase-locked loop to be synchronized with the grid. The low-frequency oscillations (LFOs) inherent in power systems will be impacted by the increasing penetration of renewable energy sources (RESs). This paper investigates the effect of virtual synchronous machine (VSM) based RESs on the LFOs in power systems. A detailed two-machine system has been used to analyze the LFOs which exists when VSMs replace synchronous generators. This paper analyzes the LFO modes which exists in an all-VSM grid. The role of the power system stabilizers in the all-VSM grid has been comprehensively evaluated. The IEEE benchmark two-area four-machine system has been employed to corroborate the results of the small-signal analysis and observe the transient performance. The analysis in this paper have been performed in MATLAB/SIMULINK environment.*

Keywords—*Virtual Synchronous Machine, Low Frequency Oscillations, Renewable Energy Sources, Power System Stabilizer, Phase-Locked Loop.*

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I. INTRODUCTION

Natural, specialized, and financial problems have arisen expanding the use of renewable energy sources (RES) in daily life within power system. The large-scale RESs in place of synchronous generators (SGs) features a noteworthy effect on power system elements and serves as vital part on the system soundness. RESs must use control paradigms that are as robust as conventional SGs to meet the 2050 target without jeopardizing grid stability and reliability. Because of this, several studies have been conducted on the design and implementation of Virtual Synchronous Machine (VSM) algorithms. These algorithms make it possible for RESs to mimic the behaviour of the SG, thereby enhancing the reliability and stability of the grid. However, because VSMs mimic SG dynamics, the VSM may also exhibit some of the undesirable characteristics of the SG. Although several studies have investigated how the VSM works in a grid, only a small number of previous studies have investigated how the VSM affects power system low-frequency oscillations (LFOs). The typical frequency range of LFOs, which are a characteristic of the conventional power system, is between 0.1 and 2 Hz. Although the term "LFO" is typically used to refer to the electromechanical oscillations produced by SGs, recent research has suggested that the interaction between RESs and SGs could produce new modes in the LFO range. The threat of LFO instability will continue to exist considering the critical role that LFOs play in maintaining the stability of the power system and the gradual substitution of SGs by RESs. Additionally, it should be noted that a "zero carbon power system" does not necessarily imply the absence of SGs. For instance, SGs are utilized in nuclear and hydropower plants, which are regarded as sources of clean energy. As a result, the oscillations in the LFO range coming from the RESs and SGs are referred to as LFOs in this paper.

Although, high recurrence motions likewise happen in the connection between RESs, the damping components on the virtual lead representative and virtual automatic voltage regulator (AVR) of the proposed VSM guarantee satisfactory damping of high recurrence motions. Limiting the magnitude of power transfer in critical tie-lines to reduce system stress is one way to lessen the impact of LFOs; however, this results in inadequate utilization of transmission line infrastructure. LFO damping has also been suggested in the literature by modulating demand side load. The main idea is to control user loads in response to LFOs from distance. To achieve adequate damping of LFOs, the loads are divided into clusters and controlled by wide-area signals for each cluster. However, to achieve satisfactory performance, this method requires significant end-user loads, which may not be readily available at the time of need. The installation of power system stabilizers (PSSs) on SGs is an efficient method for damping LFOs. The most common and cost-effective method for damping LFOs in power systems has been this one. By injecting additional stabilizing signals into the SG, the PSS reduces the effects of the LFOs and boosts system stability. The power, frequency, and speed of the rotor are frequently utilized as PSS input signals. However, the increasing use of RESs in place of SGs has raised new questions and prompted a few studies. Although the operation of RESs at the distribution level is the primary focus of this study, it is reasonable to anticipate similar trends. In the literature, there have generally been two approaches:

- Utilizing stabilizing signals on RES s to damp LFOs &
- Mitigating the impact of RESs on LFOs

A retrofit controller for wind farms employing a linear quadratic regulator and relying solely on partial feedback of states is used to reduce the impact of RESs on LFOs. This design ensures that a system that has been stable before is not destabilized by newly added RESs. Additionally, it was observed that RESs had less of an effect on LFO damping when phase-locked loop (PLL) parameters were optimized. As opposed to unity power factor control, studies show that applying voltage or reactive power control to RESs improves LFO damping and alleviates the reactive power strain on SGs. However, new LFO modes can result from the interaction of RESs' reactive power control with SGs. Additionally, the performance of the low-voltage ride-through as well as the synchronization may be affected by the suggested parameter changes to the PLL. In addition, their use of parameter optimization may not adequately dampen external disturbances emanating from the SGs due to the emphasis on reducing the negative impact of RESs on the power system. Subsequently, the main part of concentrates on RESs center around the sending of PSS and power wavering dampers (Units) utilizing both nearby and wide-region signs to sodden LFOs. However, new research is shifting its attention to the robust and grid friendly VSMs due to the traditional RESs' potential for frequency instability and inertia reduction. As a result, this paper investigates the PSS's role in system where VSMs replace SGs and the LFO modes that result.

II. METHODOLOGY

The most common and cost-effective method for damping LFOs in power system is by injecting additional stabilizing signals into the SG, the PSS reduces the effects of the LFOs and boosts system stability. To analyze the effect of Virtual Synchronous machine in power system on low frequency oscillations following two approaches are considered.

1. Utilizing stabilizing signals on RESs to damp LFOs.
2. Mitigating the impact of RESs on LFOs.

The analysis followed in this project are as follows: -

1. Comprehensive analysis on the impact of replacing SG with VSM and VSM_{PSS}, using a detailed two-machine system.
2. Comprehensive analysis of the LFO modes which exists in an all-VSM power system.
3. Evaluation of the role of PSS in an all-VSM power system.

It is noted that in this project, VSM topology uses a direct voltage-controlled approach, "dq-axis current injection" converter, which uses a "Swing-equation based inertial response".

- *VSM*

Power generation is dominated by synchronous generators. Virtual synchronous machine combines a three-phase inverter with synchronous generator behavior through a control system, ensuring stable grid operation, damping, power compensation and voltage control.

- *The structure of proposed VSM*

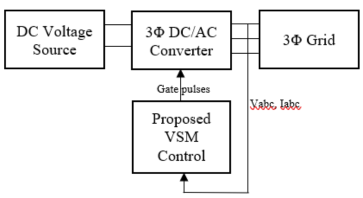

Fig 1: structure of proposed VSM control-based power system model

To enable RESs to behave like SGs, VSMs are proposed. Wind turbine applications are the basis for the VSM method used in this project. This VSM paradigm has the unique benefit of not requiring switching operations in all modes. In other words, grid connected operation, low-voltage ride-through and islanding. We can substitute any renewable energy source in place of the DC voltage source. As a result, the synchronous generator is replaced with a virtual synchronous machine system in two-machine and four-machine systems.

- *The proposed VSM control structure*

The usual dq frame current controllers are used in this. The three main components of the proposed control structure are outlined below:

- *1) Virtual governor*

The virtual governor's primary functions are to maintain a nominal frequency f. Regulating f in proportion to current demand i_d (associated with the active power P) accomplishes this. The following equation provides a description of the governor dynamics:

$$i_d^* = k_t(f^* - f)\left(\frac{1}{1+\tau_s s}\right) + i_{d-set}$$

Where f* is the reference frequency, i_d* is the equivalent current set point, and i_{dset} is the reference active current. The PLL, which supplies f to the virtual governor, operates in both islanded and grid-connected modes, ensuring that f is well controlled in all modes of operation. A Maximum power point tracking (MPPT) algorithm can be used to calculate P_{set}, which determines $i_{d\text{-}set}$. The Virtual governor's droop gains and damping filter time constant, respectively, are kf and τf. The voltage VC is aligned in the dq frame by the PLL, so V_{cq}= 0 (V_{cd} = $|V_c|$).

- *2) Virtual AVR*

The virtual AVR's function is to adjust V_{cd} in accordance with the reactive power Q and the current demand dq. The virtual AVR arrangement is where V_d^* , i_q^* , Kv and τv address the reference voltage, reference reactive current, droop gains and damping filter time constant respectively. The virtual AVR effectively controls V_{cd} for every working mode (matrix associated and islanded) and guarantees quick issue current infusion during shortcoming.

$$i_q^* = -K_v(V_{cd}^* - V_{cd})\left(\frac{1}{1+\tau_v s}\right)$$

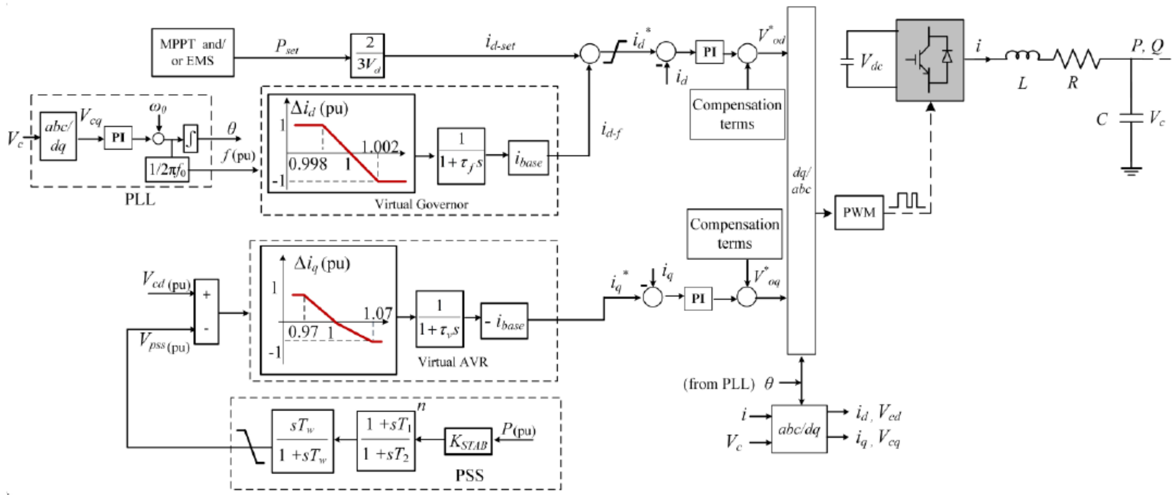

Fig 1. The controller block diagram

- *3) Power System Stabilizer*

The primary function of the PSS is to dampen LFOs, thereby enhancing power system stability. The P signal, which is a function of the difference in rotor angle $\Delta\delta$ between interconnected machines (for an inductive grid), is implemented here. This makes it possible to utilize a local variable (P) with sufficient information regarding remote signals (Δδ). The lead-lag filter, where n is the number of cascaded lead-lag filters, provides phase compensation for the damping signal. The signal washout block acts as a high-pass filter, removing steady state signals from VPSS and passing all signals in the frequency range of interest. The equation that represents the integration of PSS and virtual AVR is given by,

$$i_q^* = -K_v(V_d^* - (V_d - V_{pss}))\left(\frac{1}{1+\tau_v s}\right)$$

III. SMALL SIGNAL STABILITY ANALYSIS

The nature of the angular oscillations when the system is subjected to small disturbances is the primary concern in the small-signal stability study of power systems. The LFOs are the angular oscillations of interest. A single machine infinite bus model is regularly used to notice the strength, stability, performance, and execution of SGs. However, due to its inability to explain how the various power-generating sources in the network interact, this may not be sufficient for systems with multiple RESs. As a result, a comprehensive two-machine system has been developed for this project, providing an excellent platform for mode interaction between the SG and VSM observation and analysis.

The system's topology is depicted in Fig 2, where Stie is the power transmitted through the interconnecting tie-line and SL_1 and SL_2 represent the apparent power demand by the load at area1 and area2. The dq component of the machines' voltage and current, respectively, are referred to as V_{dq} and I_{dq}. Variables that are associated with machine 1 and machine 2 are denoted by the subscripts 1 and 2. In this study, the SG's sixth-order model was applied. All system components must be synchronized to a single reference frame to conduct the small-signal stability analysis investigation.

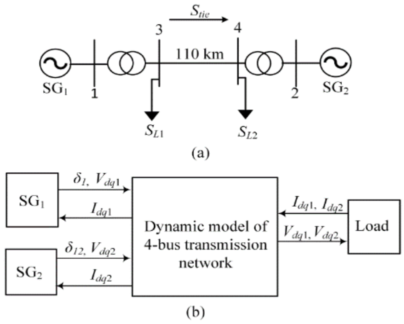

Fig 2. Two-machine system topology: (a) Single-line diagram (b) Signal-flow diagram.

Table I outlines the parameters of the system. The base rating of machine and network parameters are 1500 MVA. The transmission network and SG terminal both have nominal voltages of 230 kV and 13.8 KV, respectively.

Table I - System parameters

VSM		
Parameters	*Value*	
Current Loop PI control	Ki = 9e-3	Kp = 9e-4
tp,tf	0.005 s	1.3 s
Phase locked loop PI control	Ki = 0.05	Kp= 0.005
Filter impedance	L = 0.3 pu	R= 0.008 pu
Synchronous Generator		
Active power	1500 MVA	
Voltage (line to line)	13.8 KV	
Frequency	50 Hz	
Transformer		
Power	1500 MVA	
Frequency	50 Hz	
Primary / Secondary voltage	13.8 KV	230 KV
Rm, Lm	499.99 ohm	500 Henry
Transmission network		
Length	110 KM	
Fault duration	1.5 - 2 sec	

A. The stability analysis techniques

1. Effects of VSM replacing SG.
2. Stability of an all-VSM network.
3. PSS's role in these conditions.

1. Effects of VSM replacing SG.

Observing the LFO modes when VSMs replace SGs is the goal here. We consider three system configurations on the system to accomplish this (see Fig.2):

(1) Test system stability with two SGs (SG-SG)
(2) Using VSM in place of SG2 (SG-VSM)
(3) Expansion of PSS to VSM ($SG\text{-}VSM_{PSS}$)

The dominant system pole positions for the three test configurations are depicted in Figure 3. The dominant states and damping ratio (ζ) that influence the LFO modes are depicted in Table II. The predominant states pertaining to machines 1 and 2 are denoted, respectively, by the subscripts 1 and 2 in the final column of Table II.

1) SG and SG: The first configuration, as depicted in Figure 3(a)). It is seen that, with 2 SGs (with no PSS) the system is barely steady as a couple of poles oscillating at 5.72 rad/s are arranged exceptionally near the jω-axis. From Table II, it is seen that these poles are rotor angle modes (for example overwhelmed by , and) and ζ = 0.003. Due to a lack of damping torque, a system disturbance will result in continuous angular oscillations that do not decrease over time.

2) SG and VSM: With the VSM taking the place of SG_2 (see Fig.3(a) reveals the existence of two oscillatory poles, and The poles wavers at 2.62 rad/s and is dominated by , and (from the VSM's virtual governor). While is oscillated by and (from the VSM's PLL), it oscillates at 4.44 rad/s. Because all the poles are situated on the left-hand side (LHS) of the j-axis, this system is stable. Additionally, an increase in the damping ratio of is noted. However, its damping is still not very good (ζ = 0.092). It should be noted that, even though retuning the VSM's parameters is suggested, retuning a VSM that has already been well designed may exacerbate other modes and decrease the VSM's performance. Instead, because the VSM is made to look like the SG, some of the extra controls used on the SG, like PSS, should be used on the VSM to make the power system more stable.

3) SG with VSM_{PSS}: On the VSM, the PSS depicted in Fig.1. is utilized for this configuration. According to Fig.3(b), employing the PSS results in the introduction of an additional oscillatory mode to the system. , Vpss and dominating this mode. Additionally, the dominant modes in and are comparable to configuration 2. In any case, ΔVpss is likewise dominant on and The inclusion of the PSS shifts the oscillatory modes further to the LHS, as shown in Fig.3(b), indicating enhanced stability and damping. The ζ for in and have increased to 0.23 and 0.681, respectively, as shown in Table II, indicating that they are now well-damped.

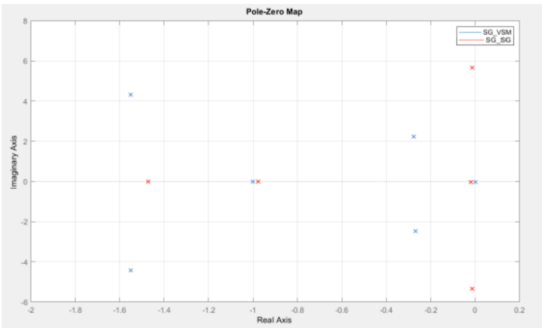

Fig 3(a) Comparison of the LFO when VSM replaces SG

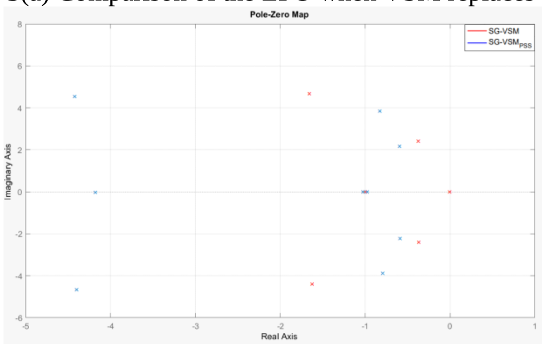

Fig 3(b) Transition of LFO modes without lead-lag compensators and with direct feedback from P.

Table II - Eigenvalues with dominance for 'Impact of SG replacement by VSM'

SG and SG			
Pole	Mode	Damping Ratio (ζ)	Dominant states
λ1,2	-0.017 ± 5.72	0.003	$\Delta\omega 1$, $\Delta\omega 2$, $\Delta\delta 12$
SG and VSM			
Pole	Mode	Damping Ratio (ζ)	Dominant states
λ1,2	-0.242 ± 2.62	0.092	$\Delta\omega 1$, $\Delta icd2*$, $\Delta\delta 12$
λ3,4	-1.58 ± 4.44	0.335	$\Delta\omega PLL2$, $\Delta\delta 12$, $\Delta icd2*$
SG and VSMpss			
Pole	Mode	Damping Ratio (ζ)	Dominant states
λ1,2	-0.584 ± 2.46	0.23	ΔVPSS, $\Delta\omega 1$, $\Delta\delta 12$, $\Delta icd2*$
λ3,4	-4.3 ± 4.62	0.681	ΔVPSS, $\Delta\omega PLL2$, $\Delta icd2*$
λ5,6	-0.87 ± 3.82	0.209	ΔVPSS, $\Delta\delta 12$, $\Delta\omega PLL2$

2. Stability of an all-VSM network.
The following are the goals here:
(a) whether an all-VSM grid has the LFO modes that were observed in SG
(b) the states that are a part of the LFO
(c) the effect that PSS has on the stability of the system.
To accomplish this, two setups are examined,
(1) VSMs take the place of both SGs in Fig.2 (VSM-VSM)
(2) PSS are added to both VSMs (VSM_{PSS} -VSM_{PSS}).

1) VSM-VSM**:** Since all the modes are located on the LHS of the j-axis, Fig. 4 demonstrates that the system is stable. At 4.44 rad/s and 6.19 rad/s, respectively, two modes are observed to oscillate. Governors and states from the PLL dominate these modes. However, has little influence on . These modes are well-damped, as shown in Table III. In addition, when this configuration is contrasted with SG-SG and SG-VSM (section titled "Effect of VSM replacing SG"), the two modes (and) are significantly more muted in the VSM-VSM configuration.

2) VSM_{PSS}-VSM_{PSS}: The system now has two more modes, and thanks to PSS's inclusion. These modes are dominated by states from the Phase locked loop, Power system stabilizer and virtual governor. It can be seen in Fig.4, which indicates that the PSS shifts the modes further to the LHS, indicating enhanced damping and stability (see Table III). The small-signal analysis reveals that the damping of interarea LFO is enhanced when SG is replaced by VSM. However, PSS is necessary for proper operation. The VSM_{PSS} is also found to be tolerant of system operating condition variations. Additionally, due to the well-damped LFO modes, an all-VSM grid can function satisfactorily without the need for a PSS. In contrast to SG-dominated grids, which do not require the PSS, an all-VSM grid can benefit from it. It should be noted that a poorly tuned VSM will not support the preceding conclusion, as it does with all control designs.

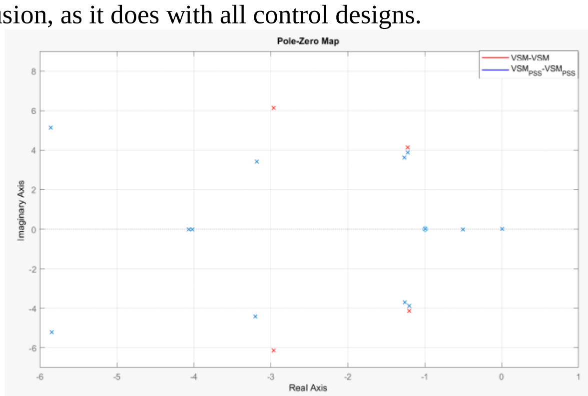

Fig 4 Effect of PSS on LFO in an all-VSM network.

Table III - Eigenvalues with dominance for 'Effect of PSS on LFO in an all-VSM network'

Pole	Mode	Damping Ratio (ζ)	Dominant states
			VSM-VSM
	-1.22 ± 4.44	0.265	,
	-2.93 ± 6.19	0.428	
			VSM_{PSS}-VSM_{PSS}
	-3.15 ± 4.49	0.575	, V_{PSS}
	-5.75 ± 5.33	0.734	V_{PSS}
	-1.42 ± 3.58	0.368	, V_{PSS}
	-1.28 ± 3.89	0.3	V_{PSS}

B. Test system's stability with 2 SGs (SG and SG)

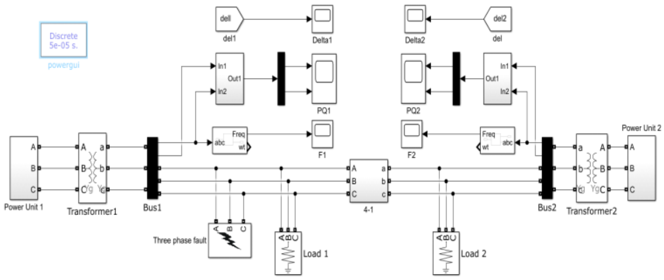

Fig 5 Simulation block diagram of two-machine system (SG-SG)

- *C. Using VSM in place of SG (SG-VSM)*

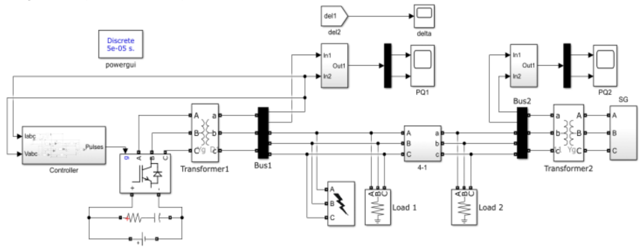

Fig 6. Simulation block diagram of two-machine system (SG-VSM)

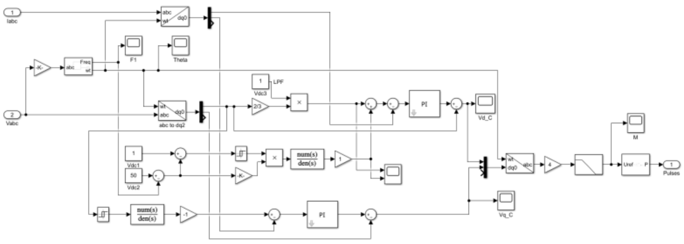

Fig 7. VSM controller

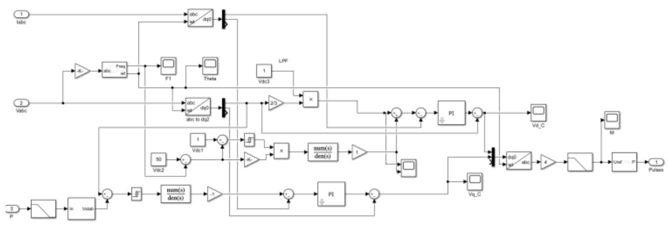

Fig 8. VSM controller with PSS

Replacing SG with VSM, reduced fault clearing time from 2sec to 0.4sec and by adding PSS to VSM further reduced the fault clearing time to 0.1 as tabulated in table IV.

Table IV - Summary of Small-Signal stability analysis

System Configuration	P(pu)	Q(pu)	δ Degrees	Fault clearing time (s)
SG – SG	0.95	0	20	2
SG – VSM	2	0	30	0.4
SG - VSM_{PSS}	1	-1	25	0.1

IV. TRANSIENT STABILITY ANALYSIS

This section aims to observe the system's dynamics in response to significant disturbances. The IEEE benchmark two-area, four-machine system, also known as the ‘Kundur model’, has been implemented to accomplish this.

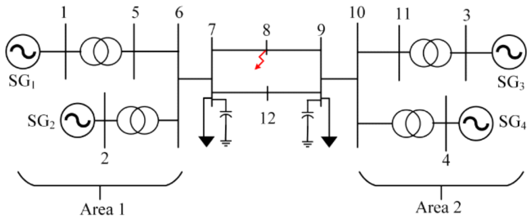

Fig 9. IEEE benchmark System with four machines and two areas

The specialized IEEE benchmark for studying LFOs and the function of PSS in power systems is this system (Fig.9). This application makes use of the SG's governor and AVR full-order MATLAB/SIMULINK model.
The following test cases were examined:

1. Impact of replacing SG with VSM.
2. Examination of an all-VSM with respect to an all-SG grid.

A. Impact of replacing SG with VSM

A three-phase fault is applied to the tie-line at bus 8 to observe the system's transient stability (see Fig.9) for 500 milliseconds at t = 1.5 s.
There are four observed system configurations.

- Four SGs without PSS (4SG)
- VSMs have taken the place of SG_2 and SG_4 (2SG- 2VSM)
- In configuration 2, PSS were added to the 2 SGs ($2SG_{PSS}$-2VSM)
- In configuration 2, PSS was added to the 2 VSMs ($2SG\text{-}2VSM_{PSS}$)

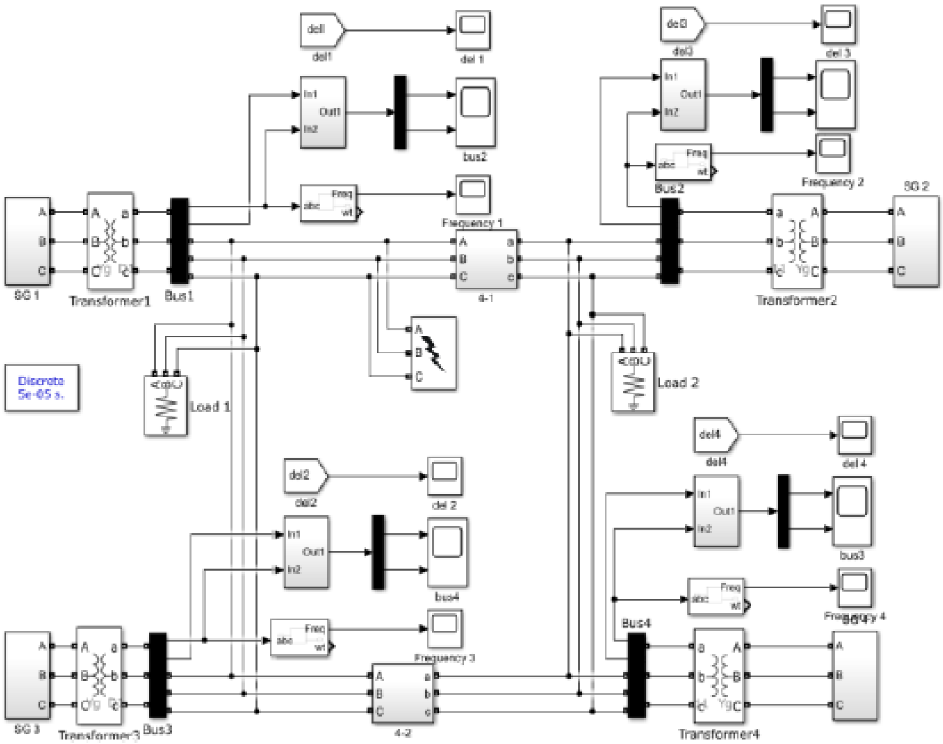

Fig 10. Simulation block diagram of 4-Synchronous Machine System

B. Examination of an all-VSM with respect to an all-SG grid

The goal is to notice the general presentation of an all-SG system in contrast with an all-VSM system. These are viewed as here to follow system arrangements.

1. Four SGs without PSS (4SG)
2. Four VSMs without PSS (4VSM)

C. Summary of Transient stability analysis
Impact of replacing SG with VSM:
Angle stability: After a fault in configuration 1, the system loses synchronization as the amplitude of the angular oscillations gradually increases, indicating that the damping torque is insufficient. The system is observed to be stable but poorly dampened in configuration 2, because the angular oscillations will take a long time to be dampened and will not increase after the fault. The system oscillations are promptly dampened out when PSS is added to the SG/VSMs in configurations 3 and 4. The PSS's performance on the VSM is observed to be very comparable to that of the MB-PSS on the SG. As a result, the VSM doesn't need a complicated PSS design to perform well.
Active power oscillation: Power oscillations in configuration 1 are observed to gradually rise after a fault as the system becomes unstable. Power oscillations do not increase in configuration 2, but they will take a long time to be dampened. Additionally, it has been observed that the SG's inertial response is more dominant, facilitating a quicker power recovery from the SG following a fault. The VSMs (P2 and P4) appear to slowly recover from the surge in power caused by the SGs (P1 and P3), preserving the system's power balance. For arrangement 3, the power swaying is expeditiously damped, and the framework keeps up with strength. The power oscillation is effectively dampened in configuration 4, and the active power dip is lower than in any of the other scenarios. This is because PSS action reduces voltage sag in tandem with an increase in Q injection, which in turn reduces voltage sag.
Reactive power injection: It has been observed that the Q injected in configuration 1 and configuration 2 are comparable, although configuration 1 has slightly less Q. In configuration 3, it is observed that, to maintain the system's Q balance, the increased Q injection on SG1 and SG3 is accompanied by the transient absorption of Q in the VSMs (Q2 and Q4). Similarly, the SGs (Q1 and Q3) in configuration 4 temporarily absorb Q because of the increased Q injection on the PSS-equipped VSMs. Configuration 4 injects the most Q during a fault in comparison to the other scenarios, ensuring the best voltage support.
Voltage: The voltage dip in configurations 2 and 3 appears to be comparable, as can be seen. Because configuration 1 injects the least Q during a fault, the voltage dip there is the greatest. Contrarily, configuration 4 exhibits the smallest voltage dip due to the maximum Q injected. This guarantees that configuration 4 provides superior voltage support to all other configurations. The stabilizing signals that the PSS injects into the system are the cause of the post-fault voltage swell and dip on configurations 3 and 4, respectively.
Frequency: During a fault, it is observed that configuration 1 exhibits the least deviation. The PSS has no effect on the frequency for configurations 2–4. It stays within the nominal value ±1% and is not impacted by the PSS. The results of this test show that replacing SGs with VSM increases the damping of inter-area LFOs. In any case, PSS is expected for agreeable execution.
Replacing SG with VSM, reduced fault clearing time from 3.5sec to 3sec and by completely removing SG from system and keeping only VSM in the system reduced fault clearing time to 0.4sec as tabulated in the Table V

Table V - Summary of Transient stability analysis

System Configuration	*P(pu)*	*Q(pu)*	*δ Degrees*	*Fault clearing time (s)*
4 SG	1.5	1.5	10	3.5
2SG – 2VSM	1.5	-1.5	20	3
2SG-2VSM$_{PSS}$/2SG$_{PSS}$-2VSM	1.5	-1.5	20	3
4VSM	2	0	20	0.4

V. CONCLUSION

The effects of VSM-based RESs on the power system's LFOs were the subject of this study. Small-signal stability was examined with a detailed two-machine state space model, and transient stability was examined with an IEEE benchmark for inter-area oscillations. An additional LFO is added to the system when VSM replaces SG, according to the small-signal stability analysis. This LFO has enough damping to not affect the stability of the system. The LFO's interaction with the SG is greatly influenced by the PLL and virtual governor from the VSM. The overall effect of replacing SG with VSM is improved LFO mode damping. However, for satisfactory performance when connected to SGs, the VSM must be integrated with PSS. For various test scenarios, the VSMPSS's robustness was confirmed. The absence of inter-area oscillations and the well-damped LFO modes of an all-VSM system render the use of a PSS unnecessary. Therefore, it is essential to use VSMs to decouple the SGs from the grid to eliminate LFOs without the need for a PSS. The analysis findings may not hold true for all topologies and a poorly designed VSM due to the wide variety of VSM algorithms described in the literature. System behavior is similar for both symmetrical and unsymmetrical fault. The two-machine test bed accurately describes the dynamics of the participating generators, as demonstrated by the close correspondence between the transient and small-signal analyses, and it can be used to investigate LFOs in VSMs with various dynamics.

FUTURE SCOPE

Power quality is an important aspects of renewable energy integration such as voltage and frequency fluctuations which are caused by non-controllable variability of renewable energy resources. The intermittent nature of RESs due to changing weather conditions leads to voltage and frequency fluctuations at the interconnected power grid and harmonics, which are introduced by power electronics devices utilized in renewable energy generation. Power grids operate with RES can be very complicated. Several capacitors can be used to maintain steady-state power factor close to unity over the output range of generators. However, these generators do not have the ability to control reactive power. Hence, VSM based intelligence control strategy can be adopted for power quality improvement in realistic power system.

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