Subsynchronous Resonance Analysis of South West Sulawesi Network with Wind Power Integration

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***Abstract*— The integration of a Wind Power Plant (WPP) is a solution to increase the reliability of the electricity supply. Moreover, it potentially affects power system dynamic operation and control. The novel features of WPP involve fluctuated wind power injection, less-inertia characteristic, and sophisticated control system alter power flow of the power system and may interact with compensator devices and the existed synchronous generators. This paper investigates the effects of WPP integration on Sub-Synchronous Resonance (SSR) of the power system. A practical test system of South West Sulawesi is investigated. Three analytical methods; frequency scanning, modal analysis, and time-domain simulations, were proposed to analyze and assess the impact of DFIG based WPP integration on the SSR. It was monitored that the DFIG based WPP contributed to enhancing the system dynamic performance. The additional power injection from DFIG based WPP might relieve the stress of the synchronous generator and reduce the transmission line congestions. The more damped situation with WPP integration resulted in mitigation of the oscillatory conditions at sub-synchronous frequency.**

Keywords—DFIG, sub-synchronous resonance (SSR), frequency scanning, eigenvalues

I. INTRODUCTION

Environmental concerns and the significant decline of fossil fuels are the two main problems that have led to the massive development of renewable energy involving wind power plants (WPP). Among wind power technologies, the Doubly Feed Induction Generator (DFIG) had the benefits over the fixed speed wind and fully rated wind energy conversion system in terms of high capacity, low cost and flexible control features [1].

The long transmission lines must transmit the generated power from WPPs since the wind farms are primarily situated in remote areas, far from existing electricity networks and the center of load. With the increased complexity of power system operation, the transmission line should handle the fluctuating power flow circumstances. Moreover, it should be able to maintain its power transfer capability under different operation scenarios. To ensure the capacity of transmission line, series compensation devices can be considered. Therefore, it offers more viable and economic solutions compared to the expansion and construction of new transmission lines [2], [3].

Even though series compensator has a beneficial impact on enhancing the capability of transmission lines, the use of series compensator devices may introduce an adverse effect on power system stability in terms of sub-synchronous resonance (SSR) [4]–[9]. The SSR can be defined as a phenomenon of energy exchange between the mechanical side of the turbine generator and network at one or more frequencies (resonance frequencies) below the synchronous frequency [10]. At resonance frequencies, the rotor current generates a magnetic field which produces the current component at sub-synchronous frequency. The sub-synchronous current components cause negative damping torque, leading to the generator shaft failure [11].

The SSR phenomenon might happen due to the integration of large-scale WPP into a power system with a certain number of compensator devices. Wind farm integration, especially the DFIG type of WPP, potentially introduces the SSR. The integration of a Wind Power Plant (WPP) is a solution to increase the reliability of the electricity supply. Moreover, it potentially affects power system dynamic operation and control. The novel features of WPP involve fluctuated wind power injection, less-inertia characteristic, and sophisticated control system alter power flow of the power system and may interact with compensator devices and the existed synchronous generators. This paper investigates the effects of WPP integration on the power system's Sub-Synchronous Resonance (SSR). A practical test system of South West Sulawesi is investigated. Three analytical methods; frequency scanning, modal analysis, and time-domain simulations, were proposed to analyze and assess the impact of DFIG on the SSR. It was monitored that the DFIG based WPP enhanced the system dynamic performance and mitigated the oscillatory conditions at sub-synchronous frequency that originated from induction generator effect, torsional, and control interactions [12]. The subsynchronous induction generator effects occurred when the magnitude of negative sequence rotor resistance of the DFIG is larger than the sum of armature and network resistance. Under this condition, the self-excitation of induced current at sub-synchronous frequency emerges [13]. The torsional interactions occur when the converter control system of DFIG interacts with the mechanical side of the generator. The interaction between DFIG control and the mechanical side of the generator potentially reduce the damping of torsional oscillations. While the interaction between the DFIG control system and the electrical network might lead to the fast growth of oscillations [10].

Many types of research have been conducted to investigate the effects of DFIG integration on the SSR of the power system. In [2], it was reported that the series compensated DFIG brought an unstable condition when the power system was subjected to small disturbance. The unstable condition emerged due to SSR modes in deficient compensation level of transmission lines [14]. Adverse impacts of DFIG integration on torsional interaction is presented in[15], [16]. It was clearly monitored that the risk of instability increased with the increased capacity of the integrated wind power plant. The inner control system of DFIG contributed to the torsional interaction and less damping performance of the power system.

Even though the negative impacts of wind power penetration on the SSR of the power system have been reported, most of the previous research employed a simple test system to investigate the WPP effects on SSR. Single machine infinite bus was the most popular test system which was considered in the previous studies. In order to provide a more comprehensive picture of SSR in a realistic scenario of a power system operation, it is necessary to investigate the effect of WPP integration on SSR in a practical power system. The obtained results are very important for a planning consideration in a future power system with penetration of renewable energy-based power plant. Moreover, it is essential to maintain the power system stability under different levels of power injection from renewable energy resources.

This paper addresses an investigation of WPP integration effects on SSR of Power systems. The practical system of the South West Sulawesi (Sulselbar) electricity network with two WPPS in Sidrap and Jeneponto areas is considered in this study. The Sulselbar electrical network is selected as a case study of the continuous development of WPP in that area. Therefore, a comprehensive study of power system stability performance involving SSR is needed to ensure stable operation of the investigated system with different WPP penetration levels. A detailed time-domain simulation would be presented to capture system dynamic behaviour in particular SSR under different WPP penetration levels.

II. SSR AND DYNAMIC MODEL OF DFIG

A. *Sub Synchronous Resonance in DFIG*

The DFIG type of WPP potentially introduces the SSR to the power system, which are originated from the induction generator effect, torsional and control interactions. In this section, those three types of SSR in DFIG are briefly presented.

1. *Sub Synchronous Induction Generator Effect (SSIGE)*

The SSIGE phenomenon emerged when the negative magnitude of rotor resistance at sub-synchronous frequency exceeds the sum of armature and network resistances. In this condition, the sub-synchronous current would increase and resulting in negative damping at sub-synchronous frequency.

In general, the stator current in a series compensated WPP can be stated as [17]:

$$i_L(t) = A\sin(\omega_s t + \emptyset_1) + Be^{-\alpha t}\sin(\omega_n t + \emptyset_2) \qquad (1)$$

Where ω_s and ω_n are the system fundamental and natural frequency of the network, respectively.

The natural frequency f_n can be defined as a function of network reactance as follows

$$\frac{\omega_n}{2\pi} = f_n = f_s\sqrt{\frac{KX_e}{\sum X}} \qquad (2)$$

Where the compensation level is stated as $K = \frac{X_C}{X_e}$. The $\sum X$ represents the entire inductive reactance as seen from the infinite bus.

The SSIGE in DFIG might occur at sub-synchronous and super-synchronous frequency range. The equivalent circuit of DFIG corresponding to sub and super synchronous resonance is depicted in Fig.1[18]. The equivalent circuit of DFIG represents the correlation between the rotor and positive and negative components of the natural electric frequencies. At sub and super synchronous frequencies, the slip at sub-synchronous (S_1) and super-synchronous (S_2) frequencies can be stated as follows

$$S_1 = \frac{f_n - f_m}{f_n} \qquad S_2 = \frac{f_n + f_m}{f_n} \qquad (3)$$

The super-synchronous slip always has a positive value. Thus, the WPP is stable at this frequency. Conversely, since the natural frequency (f_n) is less than frequency corresponding to mechanical speed (f_m), it results in a negative value to the sub-synchronous slip. In a particular condition in which the magnitude of equivalent rotor resistance exceeds the sum of armature and network resistance, the sub-synchronous current would increase. The increase of the sub-synchronous current potentially introduces negative damping to the system, resulting in oscillatory conditions at sub-synchronous frequencies.

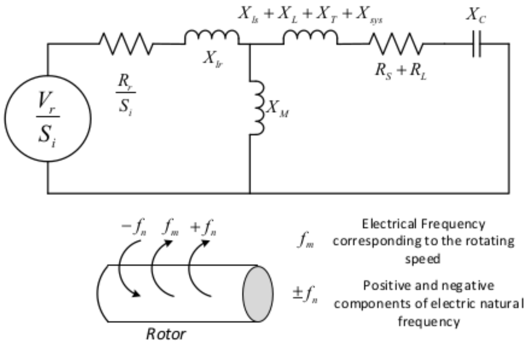


Figure 1. Equivalent circuit of DFIG corresponding to sub and super synchronous resonances

2. *Sub-Synchronous Torsional Interactions (SSTI)*

The torsional interaction between DFIG and the electrical network might occur if the natural torsional frequency of DFIG rotating drive-train and the electrical grid is close. Even though the SSTI might introduce sub-synchronous torque component to the system, the effect of WPP integration on SSTI of the power system can be neglected since the stiffness of DIFG based WPP is much smaller compared to the conventional power plant based on synchronous generator [18]. The effect of DFIG based WPP on SSTI might be considered in a very high level of network series

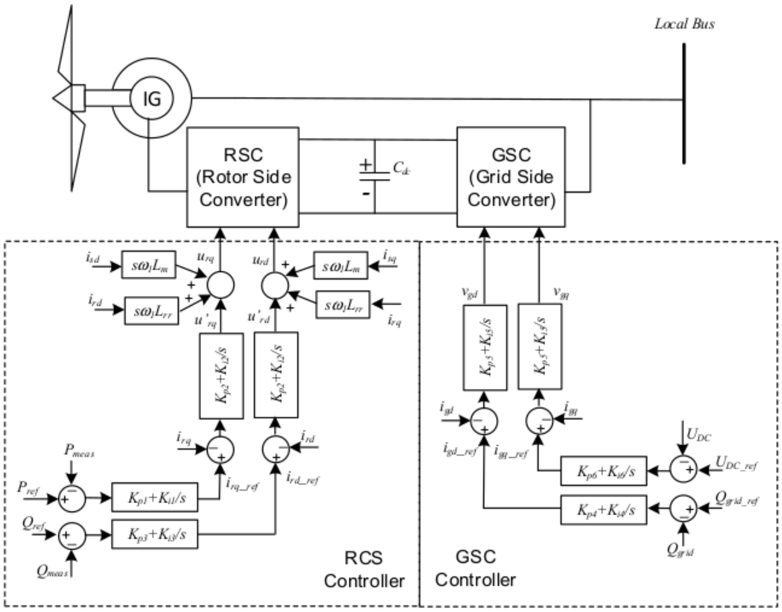


Figure 2. Dynamic Model of DFIG

compensation. While in practice, the series compensation level usually is not larger than 70%-75%. With the neglectable effect of WPP on SSTI, the stiffness effect of DFIG on SSTI is not a concern of this paper.

3. *Sub-Synchronous Control Interactions (SSCI)*

The control system is the critical part of DFIG bases WPP to ensure flexible and stable operation at different wind speeds. Moreover, it is also required to control the power flow between the WPP and electrical network. The SSCI emerged as a result of interaction between the DFIG controller and the series compensated electrical grid. The main characteristic of SSCI is the difficulty to determine the frequency range and faster growth of oscillatory conditions compared to the other two types of SSR. Those features emerged since the occurrence of SSCI not only depends on the series compensator parameter but is also affected by the configuration and setting of controllers parameters [12], [19], [20]. Moreover, faster growth of undamped oscillatory circumstances in SSCI due to the shorter time constant of the DFIG controller.

B. *Dynamic Model of DFIG*

In this research, the default model of DFIG based WPP in DigSILENT Power Factory is considered. The investigated dynamic model of DFIG is comprising of shaft model, induction generator model, rotor side converter (RSC), grid side converter (GSC), and DC-link capacitor models as depicted in Fig.2.

To facilitate analysis of DFIG based WPP impacts on SSR of power system, the mechanical side of the WPP is modeled as a multi-mass system. Therefore, in this research, two masses model is considered, and the state equation of the mechanical side of DFIG can be stated as [21]:

$$\frac{d}{dt}\begin{bmatrix}\Delta\omega_t\\ \Delta\omega_g\\ \theta_{tg}\end{bmatrix}=\begin{bmatrix}\frac{-D_t-D_{tg}}{2H_t} & \frac{D_{tg}}{2H_t} & \frac{-K_{tg}}{2H_t}\\ \frac{D_{tg}}{2H_g} & \frac{-D_g-D_{tg}}{2H_g} & \frac{K_{tg}}{2H_g}\\ \omega_0 & -\omega_0 & 0\end{bmatrix}\begin{bmatrix}\Delta\omega_t\\ \Delta\omega_g\\ \theta_{tg}\end{bmatrix}+\begin{bmatrix}\frac{\Delta T_m}{2H_t}\\ -\frac{\Delta T_e}{2H_g}\\ 0\end{bmatrix} \quad (4)$$

Where H and K are the inertia constant of each mass and the stiffness coefficient between the two ends of the shaft, respectively. The index terms of t and g refer to wind turbine and DFIG, respectively. While T_e and T_m represent the electrical and mechanical torque, respectively. The 6th order dynamic model of induction generator is considered in this paper. The detailed state variables of the induction generator in DFIG are presented in [22].

The control system of DFIG based WPP is comprising of RSC and GSC controllers. State equations of RSC and GSC controller are adopted from [19], [21]. The RSC controller is responsible for controlling the electric torque and power factor at the stator terminals. Hence it allows the DFIG to provide a stable operation under the fluctuating condition of wind speed and ensure optimal operation of DFIG under different wind speed circumstances. Active and reactive power from the input side of DFIG is compared to reference values and regulated through PI controller to provide control signals for RSC. Power flow control and regulation of DC-link voltage are facilitated by the GSC controller. The measured active power and DC link voltage and compared to the reference values and regulated using PI controller to generate the switching signal of GSC.

C. *Modal Analysis*

Sensitivities of power system can be investigated through modal analysis. It captured the dynamic behavior when power system is subjected to small perturbation. Analytical the procedure of small-signal stability can be conducted through linearization of equations associated to system dynamic response as given by the following state equation

$$\Delta\dot{x} = A\Delta x + B\Delta u \quad (5)$$

Where *A* and *B* respectively represent system state and input matrices. While state and input variables matrices are given by Δx and Δu respectively.

The dynamic performance of the power system depends on the dynamic behavior of state variables reflected in eigenvalues. Participation factor analysis is considered to measure the activity of j^{th} state variables in a particular i^{th} mode. The magnitude of the normalized participation factors for an eigenvalue *i* is stated as follows

$$P_{ji} = \frac{|\Phi_{ji}||\Psi_{ij}|}{\sum_{k=1}^{n}|\Phi_{ki}||\Psi_{ik}|} \quad (6)$$

Where P_{ji} is the participation factor, *n* is the number of state variables. Φ and Ψ represent right and left eigenvector, respectively.

III. RESULTS AND DISCUSSIONS

A practical electricity network of South West Sulawesi, Indonesia, is considered in this paper. The interconnected power system network comprising of 16 synchronous generators and two 150 MW DFIG based WPP. The WPPs are connected to buses 9 and 28 which represented Jeneponto and Sidrap areas, respectively. The detailed model of the investigated system is presented in [23]. In order to investigate the occurrence of SSR and effects of DFIG based WPP on SSR of power system, the synchronous generator were modelled as a multi mass system. DigSILENT Power Factory analytical software was used to investigate the dynamic system behavior and the occurrence of SSR with the integration of WPP.

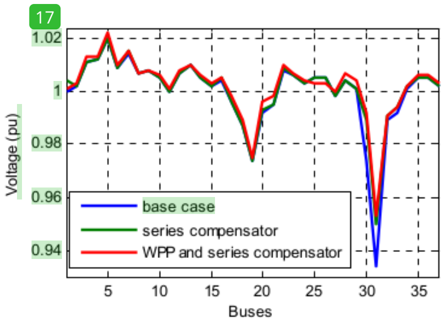


Figure 3. System voltage profiles.

Load flow analysis was conducted to make sure stable operation of the investigated power system in various scenarios. The comparison between system voltage profiles in three scenarios; base case, with series compensator, and with WPP-series compensator installation, is depicted in Fig.3. Without WPP integration and series compensator, an under-voltage condition was monitored at bus 31. To enhance system voltage profiles, particularly the under-voltage bus, a compensator was installed in series with a transmission line between bus 20 and bus 30. As a result, the under-voltage condition was solved. Further improvement of voltage profiles was observed when WPP and series compensator were considered as indicated by higher voltage profiles compared to the other two scenarios.

The installation of a series compensator might bring either advantages or detrimental effects to power system stability. As mentioned before, the series compensator helped the system to improve the voltage profiles. Conversely, it might introduce unexpected interaction between the mechanical side and network reactance at sub-synchronous frequency. Moreover, the integration of a novel power generation unit such as WPP potentially affects the power system's dynamic performance involving the sub-synchronous resonance (SSR). As mentioned above, the implementation of an induction generator, less inertia feature of power generation, and a sophisticated control system of DIFG based WPP alter the system inertia and affects the SSR.

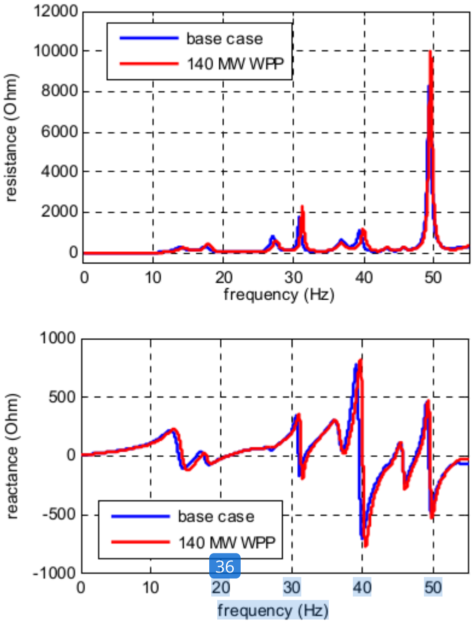


Figure 4. Impedance behind rotor circuit of generator 12.

The effect of increasing wind power on the SSR of the power system is investigated. It is considered that the percentage of series compensation is fixed while the power penetration of DFIG based WPP is gradually increased. Percentage of compensation can be defined as the ratio of the capacitive reactance of series compensator to the line reactance. In this research, the compensation level is set to 50%, and the size of DFIG based WPP is varied between 50 MW to 140 MW. The occurrence of SSR is identified using the frequency scan method. Fig.4 shows resistance and reactance behind rotor circuit of generator 12 in base case scenario and 140 MW wind power penetration at 50% compensation level. It was observed that several resonance modes were identified as indicated by spikes in the resistance figure and zero-crossing in the reactance figure. Series resonance modes were identified at 11 Hz, 12 Hz, 19 Hz, 24 Hz, 31 Hz, and 47 Hz as the reactance crossed zero from negative to the positive value. The occurrence of resonance at some particular frequencies was also identified when 140 MW wind power was integrated into the system. It was also

Table 1. Investigated sensitive eigenvalues

State variables	Eigenvalues		Damping Ratio (%)	
	Base case	**140 MW WPP**	**Base case**	**140 MW WPP**
Shaft, power angle G2	-0.40615±193.132	-0.41014±193.138	0.2103	0.2124
Shaft, power angle G3	-0.42553±189.162	-0.45816±189.155	0.2249	0.2422
Shaft, power angle G2	-0.40905±154.544	-0.41260±154.543	0.2647	0.2671
Shaft, power angle G6	-0.27477±150.677	-0.27506±150.677	0.1824	0.1826
Shaft, power angle G9	-0.08161±150.659	-0.08234±150.659	0.0542	0.0547
Shaft, power angle G10	-0.87670±125.099	-0.87673±125.099	0.7008	0.7011
Shaft, power angle G6, G7	-0.16271±75.6918	-0.16308±75.6918	0.2149	0.2156
Shaft, power angle G9, G8, G6, G5, G13, G12, G4, G3, G8	-0.20057±75.3112	-0.20162±75.3103	0.2663	0.2678
Shaft, power angle G3	-0.23156±75.4493	-0.23205±75.4452	0.3069	0.3076
Shaft, power angle G10, G15, G9, G8	-0.0995±75.3359	-0.10125±75.3365	0.1321	0.1345
Shaft, power angle G11	-0.43516±11.5437	-0.43778±11.4827	3.7669	3.8098
Shaft, power angle G1, G4, G6, G8, G9, G10	-0.45715±8.46650	-0.54659±8.43826	5.3916	6.4641

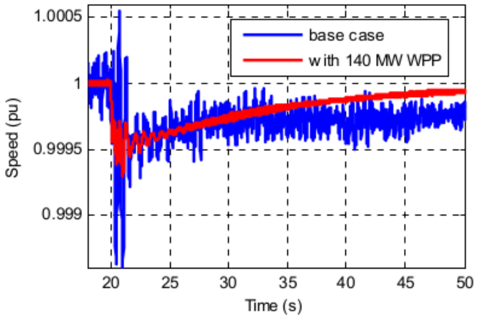
observed that even though the SSR occurred at several natural frequencies, the power system could maintain stable operations as indicated by positive values of network resistance at those frequency resonances.

Even though the occurrence of SSR can be identified through frequency scanning methods, it was challenging to assess the impact of increasing penetration of WPP on oscillatory conditions at those SSR frequencies. In order to further investigate the effect of DFIG based WPP on the SSR of the power system, the modal analysis was considered. In modal analysis, the system dynamic behaviour was investigated through trajectory and movement of sensitive eigenvalues. Moreover, damping ratio of the sensitive modes can be used as an indicator of either enhancement or deterioration of system dynamic performance.

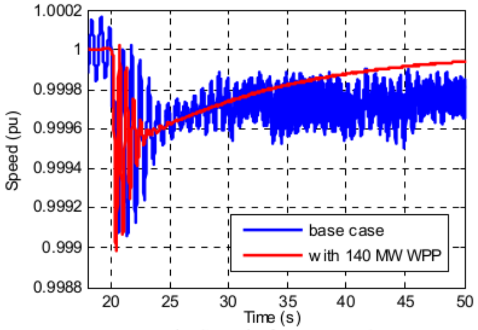
In this research, the South West Sulawesi power system consists of 16 conventional synchronous generators. The mechanical side of each generator unit was modeled as six masses systems. Therefore, there were 96 eigenvalues corresponding to generator shaft speed and power angle. The synchronous generators responded differently when the power system was subjected to small perturbation. Some generators were less sensitive to small perturbation. Therefore, only critical modes which potentially bring the system into instability were investigated in this paper. The investigated eigenvalues in base case and with 140 MW WPP penetration are presented in Table 1.

As presented in Table 1, most of the sensitive eigenvalues shifted to the left-hand side of the complex plane when 140 MW DIFG based WPP was integrated into the system. The left movement of those sensitive eigenvalues indicated improvement of oscillatory condition when power system was subjected to small disturbances. It is important to note that the additional power injection from WPP altered the power flow, reduced congestion of transmission lines and relieved the generator stress. As a result, both local and inter-area modes moved to the left as WPP power penetration increased, enhancing power system stability performances. Moreover, the improvement of oscillatory conditions is indicated by the increase of the damping ratio of the sensitive modes.

Validation of eigenvalues analysis was conducted through time-domain simulations. In order to trigger the oscillatory condition in investigated power system, a faulty condition was considered. Fig. 5 depicts the speed of generators 2 and 9 under faulty conditions in the base case and with DIFG based WPP scenarios. It was clearly monitored that the installation of series compensator devices resulted in oscillatory circumstances at several natural frequencies. As depicted in Fig.5, significant enhancement of system dynamic response was experienced when 140 MW DFIG based WPP was integrated into the system. The more damped oscillatory condition was observed when the system was subjected to three-phase faults at the 20s. It happened due to the damping contribution from DFIG based WPP to suppress the oscillatory condition of generator speed.



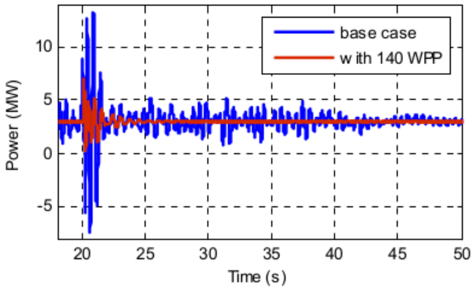
a. Speed of Generator 2



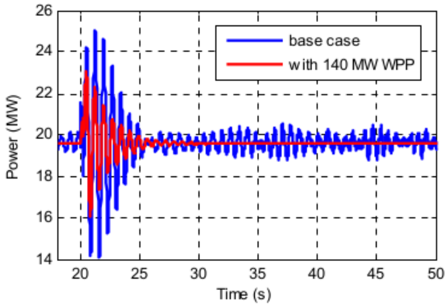
b. Speed of generator 9

Figure 5. Speed of Investigated Generator

Under the faulty condition, the output power of the generator fluctuated variously and even worse due to the occurrence of SSR. The dynamic response of output power of generators 2 and 9 is depicted in Fig.6. In the base case scenario, more oscillatory condition at the frequency resonance was monitored when the system was subjected to 150ms duration of three phase faults at 20s. Significant enhancement of output power oscillatory condition was experienced when 140ms DFIGs based WPP were integrated to the system. More damped situation was observed, resulting in a more stable power system operation.



a. Power output of Generator 2



b. Power output of Generator 9

Figure 6. Power output of investigated Generator

IV. CONCLUSIONS

The effects of DFIG based WPP on SSR of a series compensated power system is presented in this paper. A multi-machine practical test system was investigated. Three analytical methods; were considered. The frequency scanning method was proposed to identify the occurrence of SSR. Eigenvalues and time-domain simulation analysis were conducted to assess and monitor the effect of WPP integration. It was observed from impedance frequency scanning that SSR occurred at several natural frequencies. The integration of DFIG based WPP brought benefits to SSR and system dynamic response. It was clearly observed that oscillatory condition was significantly damped when 140 MW WPP was integrated, providing a more stable condition of the power system.

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