Journal of Kerbala University , Vol. 13 No.4 Scientific . 2015

Oscillation Damping in Momentarily Loss of Excitation Generators Based on Power System Stabilizers

أخماد التذبذبات الكهربائية في المولدات الفاقدة لحظياً لأثارتها بأستخدام مثبتات النظام الكهربائي

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Abstract

There are many causes that lead the generator to Loss of Excitation (LOE) such as, a short circuit in the field winding, unexpectedly open field breaker or a failure in the excitation system. LOE protection schemes are widely used to detect these faults quickly, but they remain insensitive to the external faults and for other disturbances in the power system. Power System Stabilizer (PSS) is used to measure and damp the power oscillations, which occur by cause of external faults, through the set point of the voltage regulator.

In this paper, the Multi-Band and Generic Power System Stabilizers (MB-PSS and GPSS) are been reviewed and examined in case of the generator momentarily loss its excitation, the power system must remain stable via the proposed stabilizer. The case study is based on radial power system are including: a main power station is connected with a substation across the transmission lines and a step-up transformer. The salient-pole synchronous generator is rotated by the Hydraulic Turbine and Governor (HTG) which have auto control when disturbance occurs in the power system. The performance of the power system is demonstrated by using the simulation.

Keywords: Loss of Excitation, Power System Stabilizer, Synchronous Generator, Hydraulic Turbine and Governor (HTG).

الخلاصة:

هناك العديد من الاسباب التي تؤدي الى فقدان اثارة المولد الكهربائي مثل، حدوث قصر في دائرة ملفات المجال او فتح قاطع دائرة المجال بشكل غير متوقع او فشل في نظام الاثارة. تستخدم مخططات حماية فقد الاثارة بشكل واسع لكشف تلك الاعطال بسرعة كبيرة، لكنها تبقى غير حساسة بالنسبة الى الاعطال الخارجية و للاضطرابات الاخرى في نظام القدرة. يستعمل مثبّت النظام الكهربائي (PSS) لقياس و تخميد الاضطرابات الكهربائية التي تحدث بسبب العيوب الخارجية، من خلال نقطة الضبط لمنظّم الفولتية. في البحث الحالي، تم استعراض و اختبار مثبت نظام القدرة متعدد الحزمة و مثبت نظام القدرة التقليدي في حالة خسارة المولّد لإثارتها بشكل مؤقت مع ضرورة محافظة نظام القدرة على استقراره. ان النظام المقترح قيد الدراسة يتألف من محطة رئيسية موصلة مع محطة فرعية عبر خطوط النقل و محولة رافعة. يدور المولّد التزامني نوع القطب الساكن بأستخدام توربين هيدروليكي ذاتي السيطرة عند حدوث اضطراب في نظام القدرة. إنّ أداء النظام الكهربائي قد تم وصفه بأستخدام المحاكاه.

1. Introduction:

Synchronous generators are widely used in power systems, due to their advantages such as: practically no power limitations, very high efficiency, ability to supply either inductive or capacitive requirement of the load by simply adjusting excitation, and voltage regulation (reactive power) is very simple **[1]**. Loss of Excitation (LOE) is a very common fault during operation of synchronous generator. This type of faults can occur for various causes such as: short circuit in field winding, disconnecting the field breaker or damage the relay of LOE. However, there are major damages may be produced by LOE, these damages impacts both the generator and the system as a whole.

Damages of generator can be summarized as follows: rotor overheating due to a slip frequency produced in rotor circuits, and after LOE occurs a large amount of reactive power supplied by stator current is required and may cause overheating in the stator “the generator operates as an induction machine” and the power swing will make the generator suffer from severe mechanical stress. While the damages of the system can be summarized as follows: the system voltage declines or collapses because the generator absorbs reactive power from the electrical system, the reactive power output increases from other generators in the system and may cause overloading in transmission lines or the transformers and would cause to operate the overloading relay and isolate the equipment which works without fault **[1, 2]**.

However, there are many researches done in the area of the loss of excitation in synchronous generator. **Yaghobi, et al. [3]** simulated and presented a new method for detecting LOE in synchronous generator according to the variation of the magnetic flux linkage in the air gap and monitored the effectiveness of the proposed protection with considering different generator sizes. **Gowrishankar [4]** focused on the use of advanced techniques in genetic algorithm and PID controller to tacked power system stability control problems on a single machine infinite bus system. **Balwinder, et al. [5]** compared the effectiveness of conventional PSS and proportional integral derivative PSS which are used in the system stability of a synchronizing torque among the generators. **Khalid, et al. [6]** analyzed the effect of loss of field synchronous generator on the generator and on the system and proposed a scheme to provide the loss of field protection of generator based on simple measurements at the generator terminals instead of direct detection of loss of field. **Charles, et al. [7]** discussed a specific calculation methods used to insure generator protection and excitation system control are fully coordinate, which specifically addresses the coordination of relays with generator full load capability and machine steady state stability limits and provided finally by practical guidance on providing this coordination. **Venkatesh, et al. [8]** presented a systematic procedure for modelling and simulation of a single-machine infinite-bus power system installed with a (PSS) and Fuzzy Logic Power System Stabilizer (FLPSS) and provides analytical approach is developed for the determination of PSS parameters.

In this paper, Multi-Band Power System Stabilizer (MBPSS) and Generic Power System Stabilizer (GPSS) are used and their performance efficiency are tested for keeping the power system stable in case the synchronous generator losses of excitation momentarily. The power system studied consists of synchronous generator (salient-pole type), step-up transformer, loads, transmission line and sub-station as illustrated in the **Fig. 1**. The model simulated by using MATLAB/Simulink, the parameters of the design are: continues simulation type, system operation time is 16 sec; at the period of 7.1 sec; the excitation of generator will be separated for 3 sec. The simulation results of power system will be discussed with and without use of power system stabilizers, which is mentioned previously.

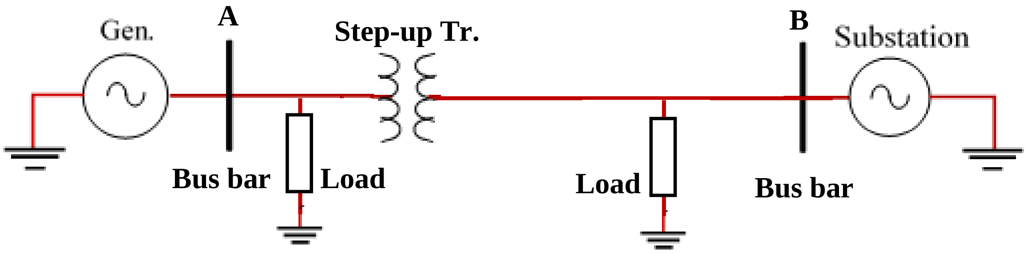

Fig. 1: Single line diagram of the proposed power system.

2.1 Generator Excitation System:

In general, the excitation system of the generator consists of an exciter and an Automatic Voltage Regulator (AVR). The excitation system works on supplying field windings of the generator by the (DC) field current to establish the rotor flux and internal voltage in the synchronous generator. Where the excitation system is enhances the power system stability by controlling the voltage and reactive power via adjusting on the field voltage. The block diagram for generator with a control unit is illustrated in **Fig. 2**.

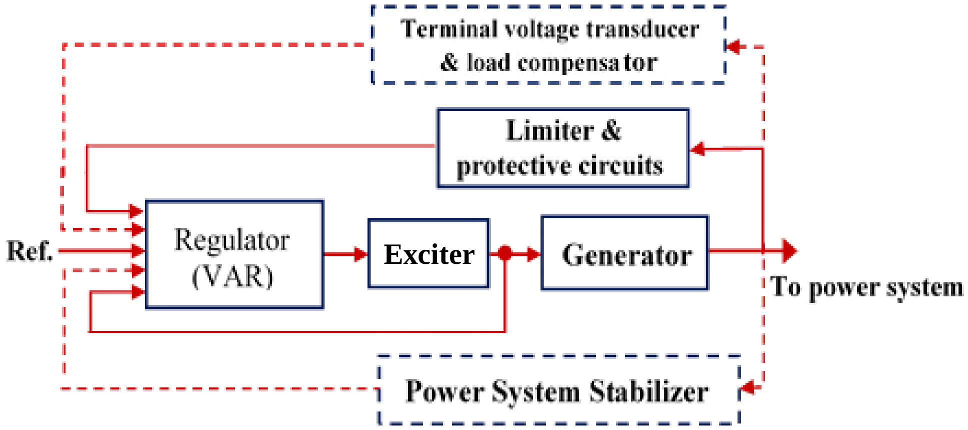

Fig. 2: Block diagram of generator with control unit system [9].

LOE able to causes in fluctuations events in the electrical network. Thus, if any generator is lost its excitation, the rotor current will decreasing and the field voltage will fall. The generator operate as an induction machine and absorb reactive power from the power system instead of supply it. According to Eq. 1, the active power output ($\mathbf{P_{out}}$) is proportional with the both of equivalent system voltage ($\mathbf{V_S}$), generator internal voltage ($\mathbf{E_{int.}}$) and the sine (**δ**).

$$\mathbf{P_{out}} = \frac{\mathbf{E\ V}}{\sqrt{X_d^2+X_q^2}} \sin \boldsymbol{\delta} \qquad \dots.\mathbf{1}$$

Where, (**δ**) is the angle between excitation voltage (**E**), and generator terminal voltage (**V**), ($\mathbf{X_d}$) the direct reactance and ($\mathbf{X_q}$) the quadrature reactance. These values of ($\mathbf{X_d}$ and $\mathbf{X_q}$) represent the positive- sequence synchronous reactance.

As the excitation voltage (**E**) of the generator is a function of generator terminal voltage (V), the output active power ($\mathbf{P_{out}}$) is also function of field voltage.

The salient pole synchronous generator can carry 15%-25% of rated load without loss of synchronization in case of LOE, causing many problems for the generator and for the electrical power system generally. For these reason, power system stabilizers are utilized to avoid the disturbances which may occur in the power grid or when LOE happens.

2.2 Multi-Band Stabilizer Power System (MB-PSS):

The main purpose from the power system stabilizer (PSS) is to add damping for the power system oscillation at operation conditions. The (PSS) is a control unit it combined with the excitation controller (AVR) in generator, to get effective damping for the oscillations in the electrical systems. The power system stabilizers can be classified to rotor angle stability, frequency stability, and voltage stability. Where the stability of voltage and frequency are related to the relation between the generating power and the power consumption in the system. So, any changing in the flow of reactive power will cause changing in the system voltage, and similar a change in flow of active power will lead to a change in the system frequency [15]. However, the (MB-PSS) is special design based on three separate bands, it dedicate to work with a low, intermediate and high-frequency modes of oscillations. All of these three bands are made of a differential band-pass filter **[10]**. Each filters has a gain and limiter, the outputs of the three bands are summed and passed through major limiter to produce the output of the stabilizer V_{stab}. The block diagram for the MB-PSS is illustrated in **Fig. 3**.

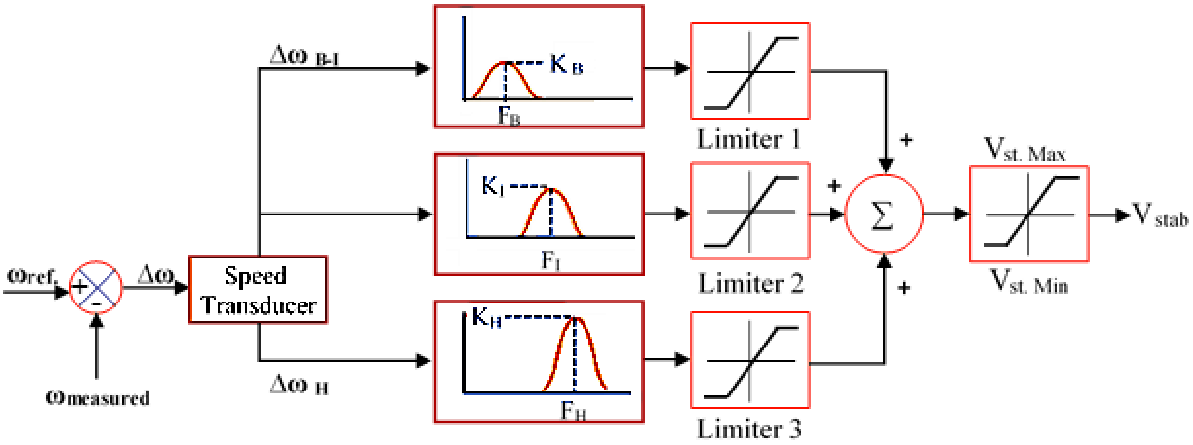

Fig. 3: Simplified schematic representation of the (MB-PSS), IEEE PSS4B [11].

The internal specifications for (MB-PSS) model (IEEE PSS4B) is illustrated in **Fig. 4**. In this model, ($\boldsymbol{\Delta\omega_{H}}$ and $\boldsymbol{\Delta\omega_{L\text{-}I}}$) are used as two different input parameters to the PSS4B. The two upper bands are designed to process low and intermediate oscillation frequencies, and the lower band is designed to process high frequency oscillations. Where two different input transducers are used to create the different input signals. These different input signals to the two different input transducers are used, depending on the (IEEE PSS4B) model as illustrated in **Fig. 5**. The rotor speed ($\boldsymbol{\Delta\omega}$) is used as direct input signal to the upper transducer, by passing the low and intermediate part of the oscillations in this transducer, the signal is injecting as the input signal to the two upper bands, low, and intermediate part of the PSS4B. But an electrical power (Pe) is used as an input to a special transducer for lower block, which represents the high frequent oscillations. However, the equation of rotor speed ($\boldsymbol{\Delta\omega = \omega_{ref.} - \omega_{mea.}}$), where ($\boldsymbol{\omega_{ref.}}$) is reference speed and ($\boldsymbol{\omega_{mea.}}$) measured speed **[11, 12]**.

Anyway, there are three main functions achieving by (MB-PSS) includes, the transducers, the lead-lag compensation and the limiters.

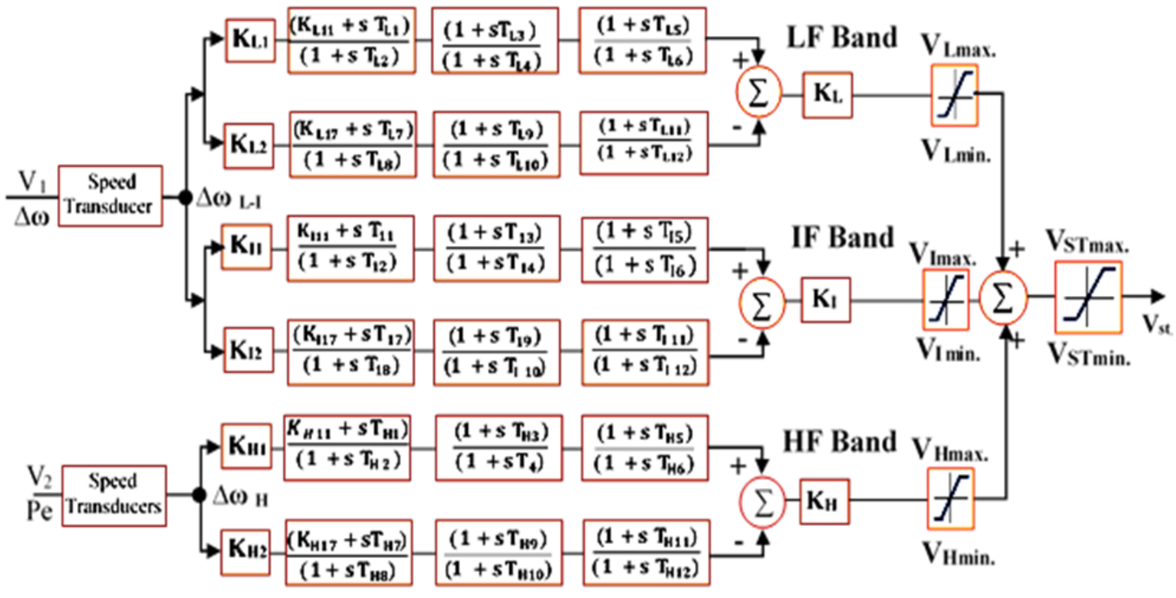

Fig. 4: The internal schematic representation of the (MB-PSS), IEEE PSS4B [11].

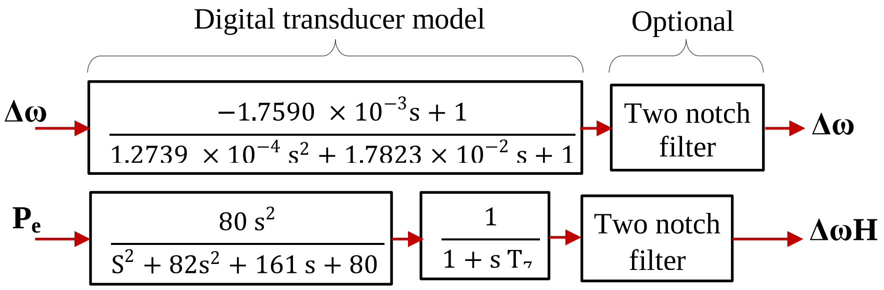

Fig. 5: IEEE PSS4B, input model of the MB-PSS [11].

There are six basic parameters to specify the lead- lag compensation circuit completely, three filters for the central frequencies F_L, F_I, F_H and three for the gains K_L, K_I, K_H. Anyway, the transfer function T(s) of the filter at (s = jω) relates the input over output signals in the s-domain. The radian frequency (ω) is a variable that represents the frequency of the sinusoidal input. After compensate the value of (s) in T(s), the transfer function T(jω) becomes a ratio of complex numbers all frequencies. In this type of filters (pass-band), the gain function has nearly constant gain for a range of frequencies. So, the time constants and gains are derived for the intermediate frequency band from the equations as:

$$\mathbf{T_{i2} = T_{i7} = \frac{1}{2\,\pi\,F_I\,\sqrt{R}}} \qquad \dots 2$$

$$\mathbf{T_{i1} = \frac{T_{i2}}{R}} \qquad \dots 3$$

$$\mathbf{T_{i8} = T_{i7} \times R} \qquad \dots 4$$

$$\mathbf{K_{I1} = K_{i2} = \frac{R^2 + R}{R^2 - 2R + 1}} \qquad \dots 5$$

Where, ($\mathbf{T_{I1}} - \mathbf{T_{I8}}$) are the symmetrical time constants, ($\mathbf{F_I}$) is the center frequency of the intermediate band, ($\mathbf{K_I}$, $\mathbf{K_L}$ and $\mathbf{K_H}$) the gains which are set to a value that gives a suitable contribution of the amplitude in each band and R is a constant ratio equal 1.2 [**13**].

To obtain a unit gain for the differential filter, branch gains (K_{I1} and K_{I2}) must be derived according to Eq. 5. Therefore the band gain is equal to Ki. In this paper, the IEEE PSS4B model in case of generator (LOE) of the MB-PSS. The impact of use PSS to damp the oscillation in the electrical grid is monitored by compared the results which obtained by using the MB-PSS with the results without using the MB-PSS for same conditions. This system is constructed from four (PSSs) and have 84 parameters, some of these parameters (time constants) such as: (T_2, T_4, T_6 and T_8) are fixed at 0.01 and the other parameters are shown in Table 1.

Table 1: Parameters of (MB-PSS).

Parameters	Values	Parameters	Values
High and intermediate speed transducer	As in Fig. 5	K_{L11} and K_{L17} (Gain)	1
$\mathbf{V_{Lmax}}$ and $\mathbf{V_{Lmin}}$ (For low freq. oscillations)	(0.0748 and − 0.0748)	T_{L2} and T_{L7}	2.076
$\mathbf{V_{Imax}}$ and $\mathbf{V_{Imin}}$ (For intermediate freq. oscil.)	(0.58 and − 0.58)	T_{L1} and T_{L8}	(1.728 and 2.5)
$\mathbf{V_{Hmax}}$ and $\mathbf{V_{Hmin}}$ (For high frequency oscil.)	(0.58 and − 0.58)	T_{H1} and T_{I1}	(0.01513and 0.174)
$\mathbf{V_{STmax}}$ and $\mathbf{V_{STmin}}$ (For stable limiter)	(0.15 and − 0.15)		

2.3 Generic Power System Stabilizer (GPSS):

The function to use the Generic Power System Stabilizer (GPSS) is controlling the excitation current for the synchronous machine through adding the suitable damping on the rotor oscillations. The electrical power system is exposed to many disorders that lead to inducing an electromechanical oscillations of the electrical generators.

These oscillations are causing instability in the power supply and may lead to risks on both of consumer and the generating units. Therefore, the active damping of oscillation is much important to reduce the risks and get a stable system. So, the input signal to the (GPPS) may be the deviation of machine speed (dω) or its acceleration power, the (GPSS) is illustrated in the **Fig.5**.

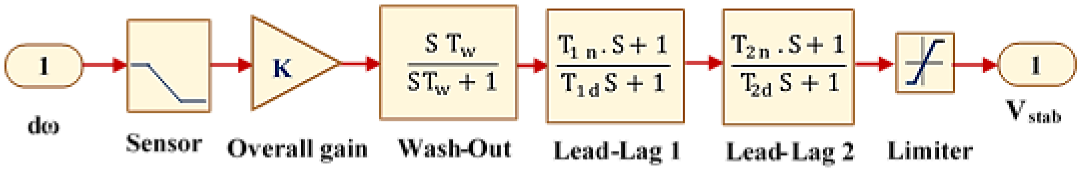

Fig. 5: Schematic representation of generic power system stabilizer [13].

The GPSS include of a low-pass filter, overall (general) gain, wash-out high-pass filter, phase-compensation system, and an output limiter. The amount of damping which produced by the stabilizer, determined in the general gain (K). A low frequencies that present in the (dω) signal are eliminating by washout high-pass filter, which allows the PSS to responding only to speed changes. The compensating of phase lag between an excitation voltage and the electrical torque of the synchronous machine, achieved through the phase compensation system which represented by consecutive of two transfer functions for first-order lead- lag as show in the (1 and 2) stages **[13, 14]**. So, the mathematical formula of ($V_{stab.}$) as in Eq. 6:

$$\mathbf{V_{stab.} = K \frac{S\,T_w}{ST_w + 1} \frac{T_{1\,n}.S + 1}{T_{1\,d}\,S + 1} \frac{T_{2\,n}.S + 1}{T_{2d}\,S + 1}.\Delta\omega \qquad \ldots 6}$$

Where, (n) order of the filter, (S) Laplace operator, (T_w) washout-time constants and (T_1&T_2) time constants. Now, in this filter, tuning of the time constants (T_1 and T_2) can be performed based on the phase shift (ϑ_1) in degrees and the angular frequency (ω_1) in rad/s of the selected eigenvalue, as in equations below.

$$\mathbf{T_1 = \frac{1}{\omega_1} \tan\left(45^o + \frac{\vartheta_1}{2n}\right) \qquad \ldots 7}$$

$$\mathbf{T_2 = \frac{1}{\omega_1} . \frac{1}{\tan\left(45^o + \frac{\vartheta_1}{2n}\right)} \qquad \ldots 8}$$

The base work for (GPSS) is monitoring the power fluctuations, by compare an input mechanical power (P_m) of the generator with its electric power output (Pe), as in Eq. 9.

$$\mathbf{P_a = P_m - P_e \qquad \ldots 9}$$

The relationship among the changing quantities to the mechanical power, electrical power, accelerating power and speed of rotor are illustrated in the **Fig.6**.

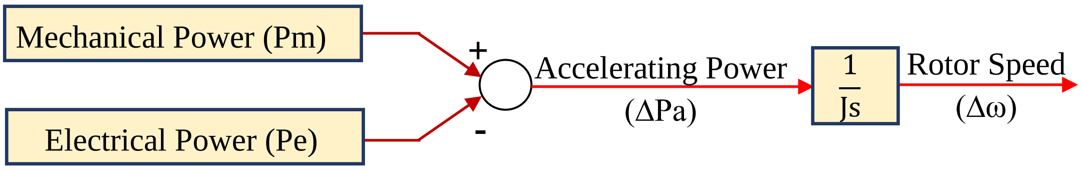

Fig.6: The relationship between the changing quantities.

The integral of mechanical power (P_m) can be derived from measured electric power (P_e) and speed of rotor (ω) or frequency as shown in Eq. 10.

$$\mathbf{\int \Delta P_m dt = \int \Delta P_e dt + J\,\Delta\omega \qquad \ldots 10}$$

Where, J is an inertia constant which equal 2H, and (H) is the time constant in second.

3. Simulink Model and Simulation Results

3.1 Simulink Model

The complete simulink model of power system with (MB-PSS and GPSS) are illustrated in the **Figs; (8** and **9)** respectively. In this model, the block of Hydraulic Turbine and Governor has been replaced by a constant value which represent the input mechanical power to the generator in pu; since it is not a field of study in this research. This constant value is equal to 150.32 MW or 0.7516 pu; depending upon specifications of the generator. According to IEEE recommended practice for excitation system models, the block diagram for an excitation system of generator is illustrated in **Fig.** 7. This system consists of two main elements, the voltage regulator and the D.C exciter. In this design, the terminal (V_{ref}) represent the desired value of the stator voltage, where the controlling on this voltage is achieved through timer and switch, thus the excitation voltage will be controlled. The inputs (V_d and V_q) are the components of the terminal voltage, and the input terminal ($V_{stab.}$) used to get additional stabilization for power system oscillations by connecting one type of PSS as in this research. The transfer function of the exciter system is represented as:

$$\frac{V_{fd}}{e_f} = \frac{1}{K_e + s\,T_e + s(V_{fd})} \qquad \dots 11$$

Where, $S(V_{fd})$ is a nonlinear function represents the magnetic saturation of the exciter system, this saturation function represents as: $s(V_{fd}) = Ae^{BV_{fd}}$, where A and B are the fitting parameters related with the normal stress and the saturation.

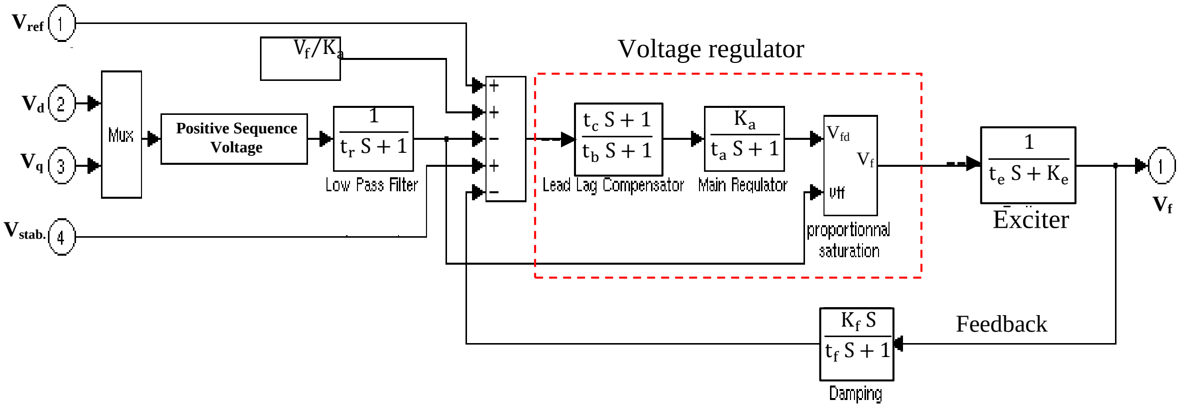

Fig. 7: Block diagram for the excitation system [9].

3.2 Simulation Results

The results of power system without PSS are compared with the results of power system with use of MB-PSS and the GPSS. There are several parameters are depended in the compare, such as: A 3- phase current for synchronous generator, the active and reactive power, output voltage of the generator, and rotor speed of generator. The comparison is based on the oscillation stabilization time. Anyway, the simulation parameters which used in the design are continuous type and all values are in per unit system.

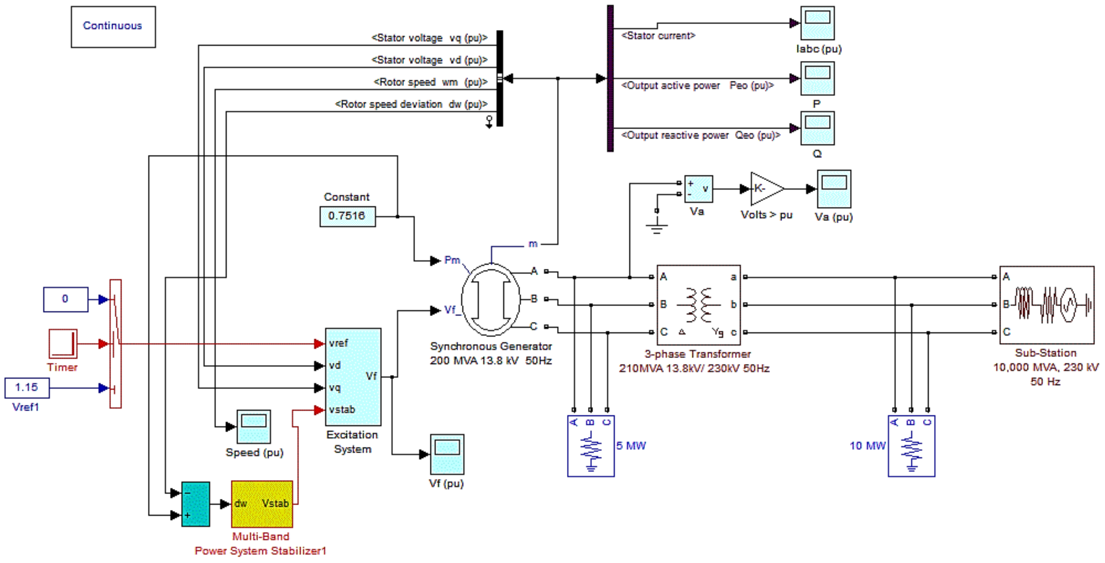

Fig. 8: Simulink model of the proposed power system with (MB-PSS).

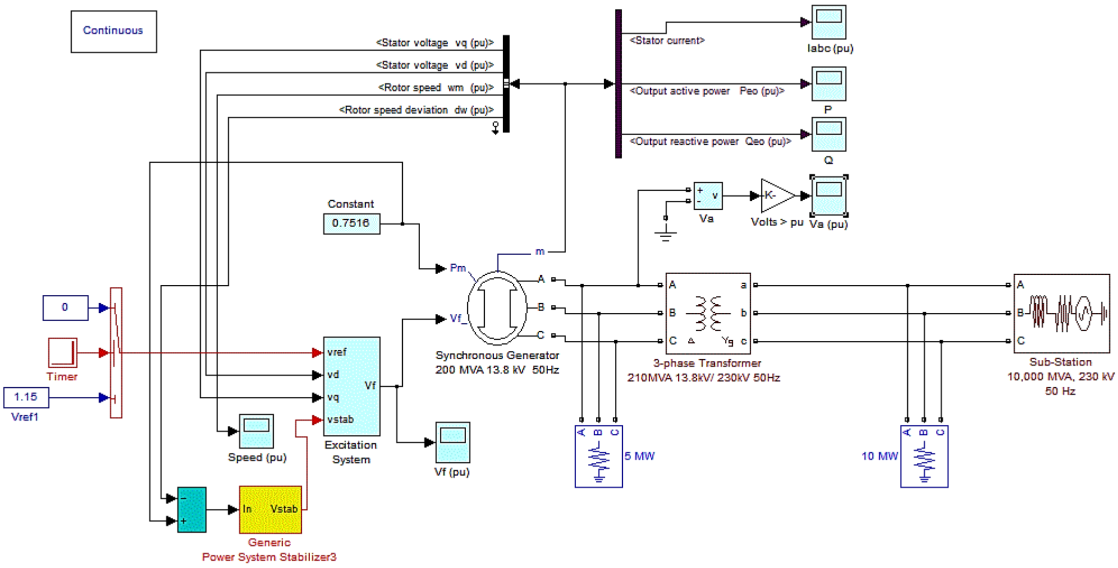

Fig. 9: Simulink model of the proposed power system with (GBPSS).

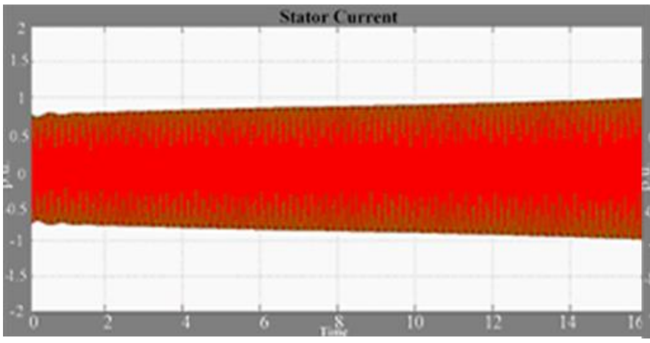

Fig. 10: Stator current of the generator with MB-PSS.

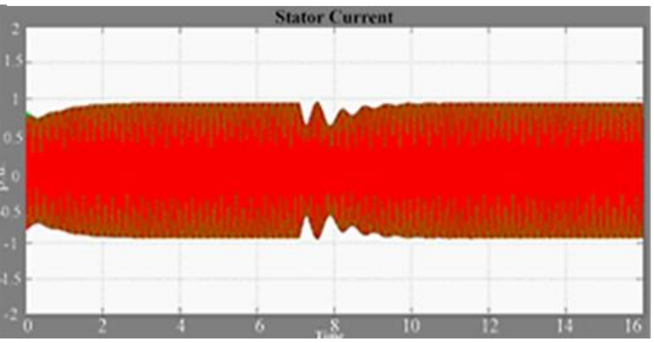

Fig. 11: Stator current of the generator with GPSS.

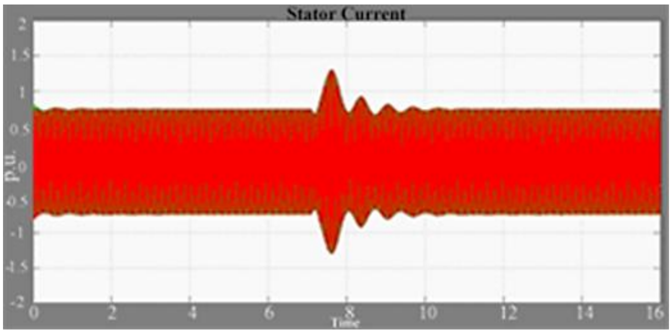

Fig. 12: Stator current of the generator without PSS.

In Fig. 10, the settling time and a maximum overshoot to the generator at starting are equals to 1 Sec; and 25% respectively. When a LOE occur, the time stability and a maximum overshoot are approximately 0 Sec; and 0%. In Fig. 11, the settling time and a maximum overshoot to the generator at starting are equals to 1.8 Sec; and 19% respectively. When a LOE occur, the time stability and a maximum overshoot to the generator are about 3.2 Sec; and 5.55%.

In Fig. 12, the settling time and a maximum overshoot are about 1.7 Sec; and 13.3% respectively, while time stability and a maximum overshoot to the generator at LOE are about 3.3 Sec; and 86%.

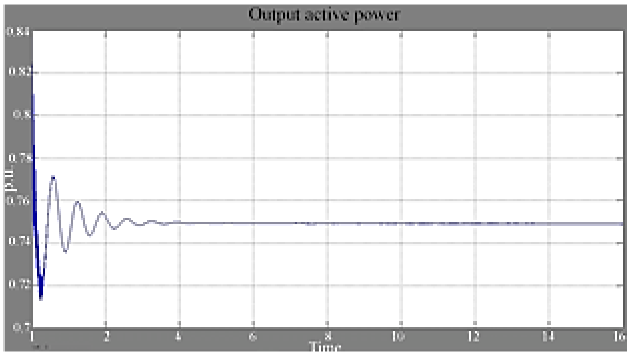

Fig. 13: Active power of the generator with MB-PSS.

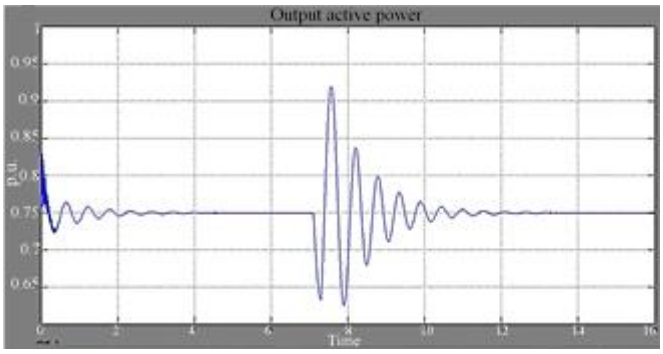

Fig. 14: Active power of the generator with GPSS.

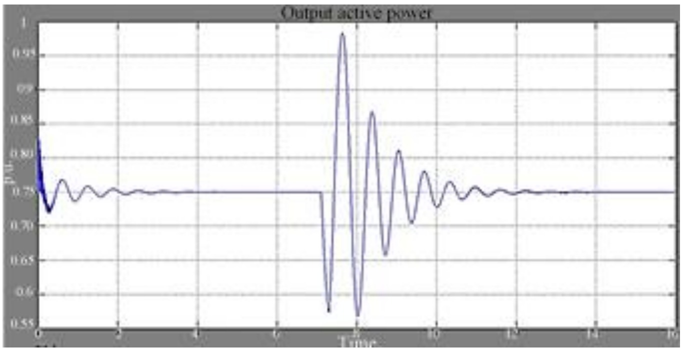

Fig. 15: Active power of the generator without PSS.

In Fig. 13, the settling time and a maximum overshoot to the generator at starting are equals to 4 Sec; and 10% respectively. When a LOE occur, the time stability and a maximum overshoot are equals to 0.7 Sec; and 0.27%. In Fig. 14, settling time and a maximum overshoot to the generator at starting are equals to 3.8 Sec; and 13.3% respectively. When a LOE occur, the settling time and a maximum overshoot are equals to 5.9 Sec; and 9.33%. In Fig. 15, the settling time and a maximum overshoot to the generator at starting are equals to 5 Sec; and 10% respectively. When a LOE occur, the time stability and a maximum overshoot are equals to 5.9 Sec; and 30.7%.

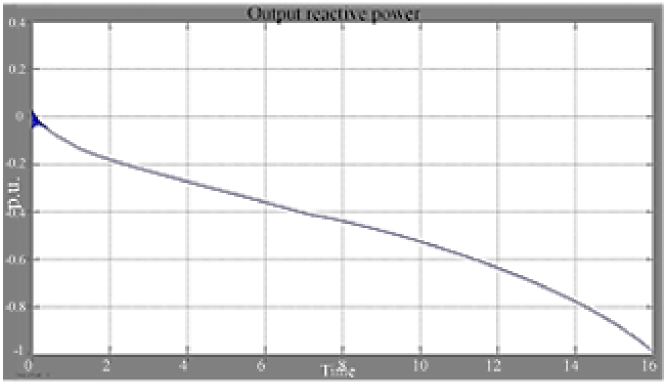

Fig. 16: Reactive power of the generator with MB-PSS.

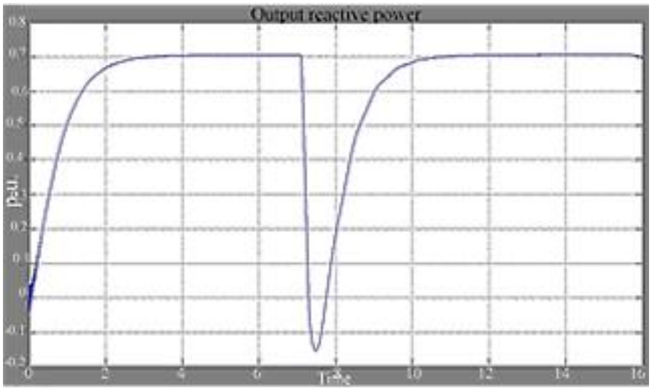

Fig. 17: Reactive power of the generator with GPSS.

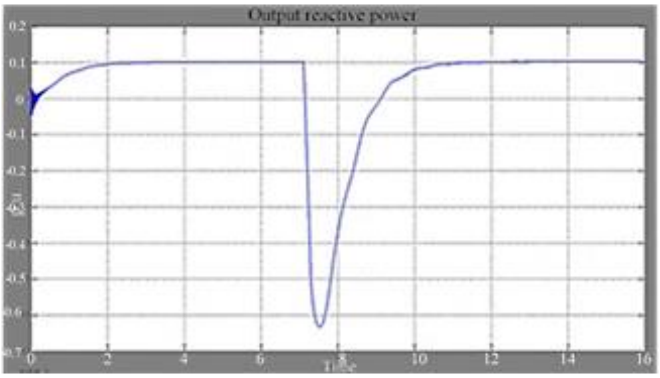

Fig. 18: Reactive power of the generator without PSS.

As in Fig; 16, the value of reactive power is Low, this means the generator is normally work and unaffected when LOE occurred. In Fig. 17, The value of the reactive power increased at starting from 0 to 0.2 p.u at time 2.8 Sec. At a LOE this reactive power is reduced to a -0.15 p.u; the settling time of reactive power is 3.1 Sec. In Fig. 18, the settling time of the reactive power at starting is 2 Sec; while its value 0.1 p.u. are equals to 2 Sec, but at a LOE occur the settling time of the reactive power of the generator is equal to 3.4 Sec.

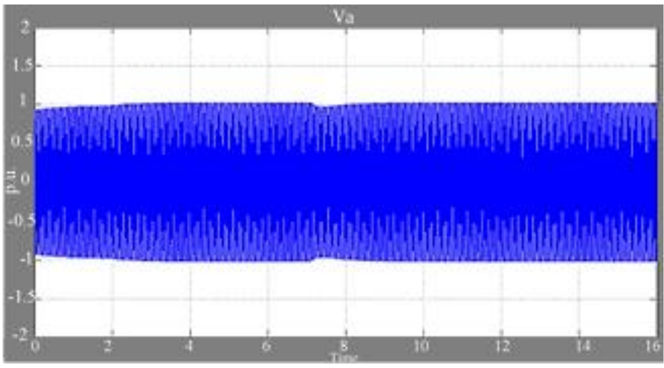

Fig. 19: Voltage output of the generator with MB-PSS.

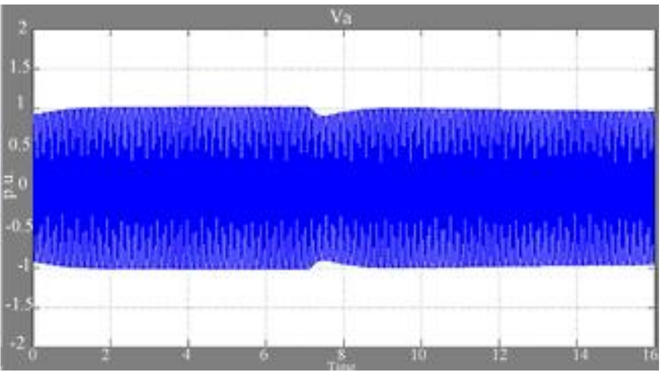

Fig. 20: Voltage output of the generator with GPSS.

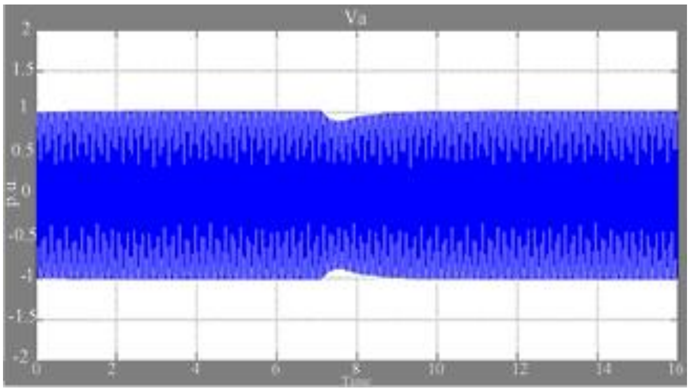

Fig. 21: Voltage output of the generator without PSS.

As shown in Fig. 19, the settling time of the output voltage for generator at starting is 0.2 Sec; but at a LOE this voltage is decreased to 0.8 p.u; the settling time is equal to 0.7 Sec. In Fig. 20, the settling of the output voltage for generator at starting is 0.1 Sec; but at a LOE this voltage is decreased to 0.7 p.u; the settling time ise equal to 1.1 Sec. In Fig. 21, the value of output voltage for the generator is 1 p.u; the settling time of the at starting is equal to 0 Sec; but at a LOE this voltage is decreased to 0.65 p.u; the settling time is equal to 1.6 Sec.

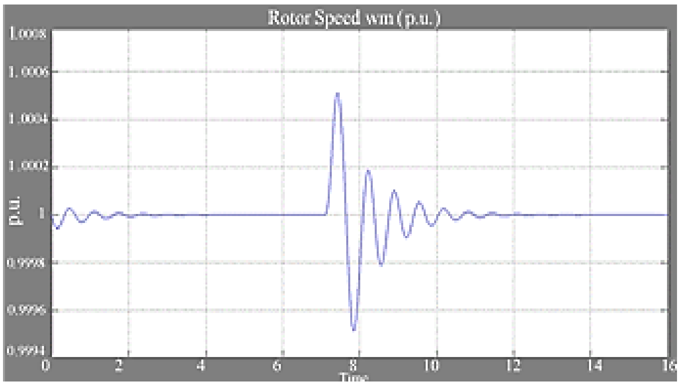

Fig. 22: Rotor speed of the generator with MB-PSS.

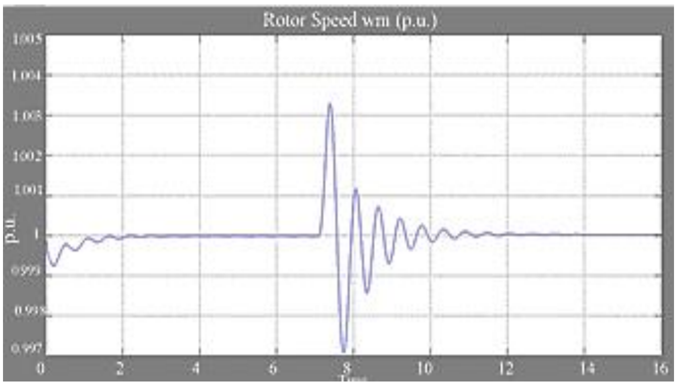

Fig. 23: Rotor speed of the generator with GPSS.

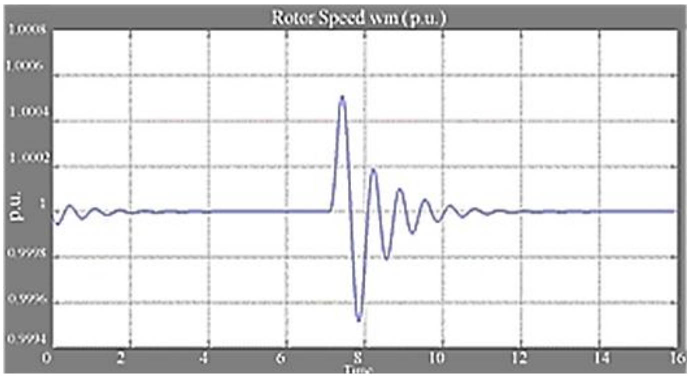

Fig. 24: Rotor speed of the generator without PSS.

As shown in Fig. 22, the settling time and the maximum overshoot to rotor speed of the generator at the starting are equals to 2.1 Sec; and 0.003% respectively. At a LOE, the settling time and a maximum overshoot are about 3.8 Sec; and 0.55 %. In Fig. 23, the settling time to the generator at starting is equal to 2.2 Sec; while the settling time and a maximum overshoot at a LOE are equals to 4.8 Sec; and 0.35%. In Fig. 24, the settling time and a maximum overshot of the voltage output to the generator at starting are equals to 3.2 Sec; and 0.05%. While the settling time and a maximum overshoot are equals to 5.7 Sec; and 0.0055%.

6. Conclusion:

This paper proposes a power system model that uses two types of power system stabilizers (the multi-band and generic). The MB-PSS is superior over the GPSS in providing significant damping to all modes of oscillation, because its structure is based on multiple stages with three separate bands. Therefore, it is able to damp effectively the low, intermediate, and high-frequency modes of oscillations. The PSS is effective for damping of oscillation in the momentary LOE (locally faults). The approximate values of the damping and the settling time for the stator current, the active power, output voltage, and the rotor speed according to the results are 95-100% and 2-3 Sec; respectively.

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