INVESTIGATING THE IMPACT OF POWER SYSTEM STABILIZERS IN A MULTI MACHINE SYSTEM WITH AN INDUCTION MOTOR LOAD

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Abstract—The high reactive power demand by the induction motor load during fault condition due to reduced bus voltages may cause a generator to behave like a voltage source behind the synchronous reactance and its terminal voltage reduces leading to the possibility of a voltage collapse scenario. For reliability of these systems, and in an attempt to reduce system oscillations, Power System Stabilizers (PSS) have used to add damping by controlling the excitation system. Studies on a SMIB and those using static loads have shown that a well-tuned PSS using a Fuzzy Logic Controller (FLPSS) can effectively improve power system dynamic stability.

This paper investigates the impact of the FLPSS in maintaining voltage stability in a system with induction motor loads. A large induction motor is introduced as a load in a multi machine system, and the impact of the FLPSS are investigated by introducing a temporary three phase fault. For comparison the FLPSS is compared to other PSS found in literature. Results indicate that the FLPSS may lead the generator to lose its capability to maintain constant voltage and hence lead to the stalling of the induction motor load soon after the fault is cleared.

I. INTRODUCTION

Current trends indicate that modern power systems are continuously working under stressed conditions. Power demand is rising constantly while several generators are connected to work synchronously to meet the demand. Occasionally, faults within a system occur, which induce electromechanical oscillations of the electrical generators. These oscillations, also called power swings, must be effectively damped to maintain the system stability [1]. Additionally, due to these faults, bus voltages are reduced, which results in voltage instability.

To facilitate reliable damping of power swings, various power system stabilizers (PSS) have been developed. To provide damping, the PSS must produce a component of electrical torque on the rotor which is in phase with speed variations. This is accomplished by generating a supplementary stabilizing signal, which is applied to the excitation system or control loop of the generating unit to produce a positive damping. The PSS design is based on the linearised model of the power system [2]. The conventional PSS (CPSS) has been shown to give poor performance under different synchronous generator loading conditions and in practical power systems which are highly non linear [3, 4].

In recent times, fuzzy logic techniques have been applied for a number of studies in power systems [5]. The techniques are highly flexible, easily operated and revised, thus suitable especially for complicated power systems with many variables. These advantages have been thoroughly researched on in various papers.

In [4, 6] the performance of the FLPSS has been investigated in an single machine infinite bus system (SMIB) and shown to be superior to the CPSS. Reference [7] analyzes the impact of an Adaptive FLPSS both on SMIB and multi machine system and demonstrates superiority to the traditional PSS. In reference [8] a study is conducted on the influence of the FLPSS on a simulation study on a four- machine power network and demonstrates the enhancement of the transient stability of the system. Reference [9] utilizes the optimization capabilities of Genetic Algorithms to tune the FLPSS, resulting better coordination of FPLSS operating simultaneously in the same power system. A proposal by [10] of a Robust Fuzzy Logic PSS (RFLPSS) that utilizes only one measure input, speed deviation, is analyzed and shown that this provides sufficient damping torque for synchronous generator unit with extra enhanced in rise time, settling time and maximum overshoot. An investigation on the influence of various membership functions on the damping capability of the FLPSS is carried out in [11], the results indicating that the triangular membership functions result in superior damping capabilities. The impact of the FLPSS in a multi-machine power system with induction motor loads has not been studied previously.

This paper investigates the capability of the FLPSS to maintain voltage stability in a power system with induction motor loads. The paper seeks to show that the FLPSS is inferior to other PSS found in literature in preventing the stalling of a induction motor load when the load is subject to a temporary fault. The simulation has been implemented in Simulink®.

II. METHODOLOGY

A. *Automatic Voltage Regulator (AVR)*

Active and reactive power capabilities of synchronous generators are crucial in achieving voltage stability in a power system. And in close relation to this, it is important for voltage stability, to have enough buses with constant voltages [12]. Synchronous generators maintain constant terminal voltages by the use of automatic voltage regulators (AVR). The AVR controls the terminal voltage by adjusting the generators exciter voltage. It does so by keeping track of the generator terminal voltage all the time and under any load condition. The AVR quality influences the voltage levels during steady state operation, and also reduces voltage oscillations during transient periods, affecting the overall system stability.

It has been demonstrated that due to power systems being highly non-linear systems, with configurations and parameters that change with time, that the CPSS cannot guarantee its performance in a practical operating environment [4].

This research compares a rule-based fuzzy logic approach to the common control techniques to a Generic PSS [2] using the speed deviation Δω as input, a Generic PSS using the power acceleration P_a as input and a Multiband PSS [13]. The design of the FLPSS is extensively explained in [8, 11,14].

B. *Induction Motor Dynamics*

Fig. 1 below shows a simplified induction load-bus test system. It is assumed that the reactive power capability of the system is infinite, that is, the generator terminal voltage *V* is constant. This numerical example serves the purpose of illustrating the process of voltage collapse in an induction motor load. The parameters of the system with an induction motor load may be found in [16].

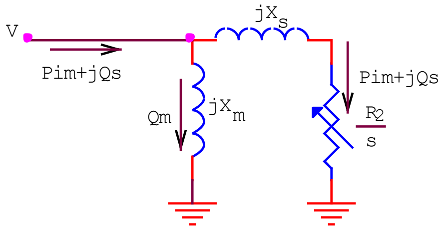

Figure 1 Induction Motor Load

The critical voltage V_{crit} at the induction motor bus when $P_{rated.im} = P_0$ is given by [15].

$$V_{crit} = \sqrt{2P_0X_s} \tag{1}$$

The maximum power loading of the induction motor while maintaining stability is given by

$$P_{\max} = \frac{V_{rated}}{2X_s} \tag{2}$$

From the equivalent model, the following equations result [16]

$$Q_m = \frac{V_{rated}^{\;2}}{X_m}\ , \tag{3}$$

$$P_{im} = \frac{V_{rated}^{\;2} \times R_2 \times s}{R_2^{\;2} + s^2 X_s^{\;2}}\ , \tag{4}$$

$$Q_s = P_{im}\frac{s}{s_{crit}}\ , \tag{5}$$

$$Q_{im} = Q_m + Q_s\ , \tag{6}$$

$$s_{cr} = \frac{R_2}{X_s}\ . \tag{7}$$

Assume sub-station terminal voltage V is varying while motor developed power is equal to the mechanical power and is constant $(P_{im} = P_{mech} = const)$. The power rating of generating station is assumed to be much greater than the rated power of the induction motor.

It is important to note that the voltage of the sub-station may vary independent of the reactive power demand of the induction motor load. A temporary fault at the substation will lead to reduction in the bus voltages. The equations (1-7) result in the curves in Fig 2.

Label 1 and label 2 in Fig. 2 represents the stability region of the induction motor load. Label 2 represents the voltage stability limit. Beyond label 2 and 3 the induction motor goes to stand still at its critical voltage. In Fig. 2 the curve labeled origin-3-5 is the demand for reactive power when the induction motor is stalling.

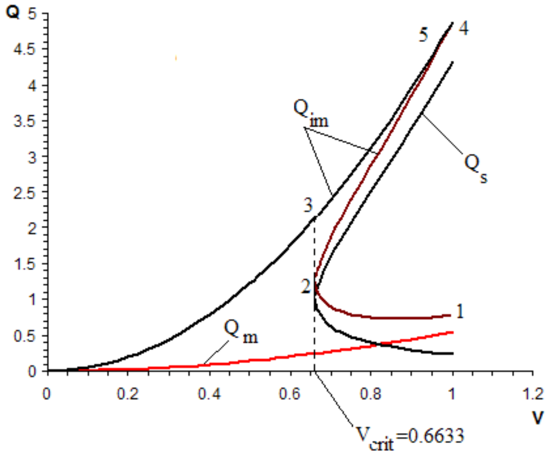

Figure 2 Reactive Power Demand for an Induction Motor Load

As seen in Fig 2., V_{crit}=0.6633pu, is the stability limit of the induction motor load. The recommended undervoltage protection for induction motor loads is 0.75 pu [17]**.** Beyond the stability limit, the induction motor becomes unstable and may stall (s=1). When the stability limit is exceeded, the demand for reactive power continues as indicated in Fig 2. By the curve labeled origin-3-5. When V=1, the demand for reactive power in the induction motor is about 5 times greater than its rated power. If the induction motor is not cut out from the supply, the large current flowing in it can damage the windings and insulation.

The induction motor dynamics may be expressed as

$$\frac{ds}{dt} = \frac{1}{2H}(T_m - T_e) \quad (8)$$

H – per unit inertia constant
T_m – Load torque
T_e – Torque developed

When a three phase fault occurs at the terminals of the induction motor, the terminal voltage of the motor becomes zero and thus the torque developed by the motor (T_e) also becomes zero. The dynamics of the motor during the faulted period is given by

$$\frac{ds}{dt} = \frac{1}{2H}(T_m) \quad (9)$$

By integrating the above equation and setting the initial slip as s_0 and the critical slip as s_{cr} we can get the critical clearing time as

$$t_{cr} = \frac{2H}{T_m}(s_{cr} - s_0) \quad (10)$$

s_0 – initial slip

This research studies the effects of the excitation system, usually ignored or over simplified in voltage stability studies, like in illustration above. For voltage stability, it is important to maintain constant voltages in enough buses in the system. The fast response of modern AVR of generators are crucial in achieving these constant voltages.

III. CASE STUDY

A. *Test System Description*

For the study the 16 bus system, Fig 3., from literature was used [3].

It consists of nine lines, three generators, and seven load points. The three generators are a steam plant located at Rogers, a hydrogenation plant at Russel Dam and a tie line to an external system connected at Lowry substation. The cities Grigsby, Feasterville, Philipsburg and Honnell represent the major load centers. The hydrogenation plant at Russel Dam and the steam plant at Rogers also take significant loads from the system. The parameters of the system may be found in [3].

The system was modeled in Simulink®. This system was stable and could perform load flow and thus formed a perfect platform for introducing a fuzzy logic based PSS and assess its impact on the system after various fault. For comparison on the effectiveness of the fuzzy logic based PSS other stabilizers, found in literature, are analyzed as well.

A 2250HP induction motor load with under voltage protection set at 0.75pu replaced part of the static load at bus 3. The system was subjected to a temporary three phase fault at bus 3. The impact of the fault on the mechanical power, the field voltage of the machines, the motor speed and the reactive power demand and generated were plotted against time under various stabilizers.

The total simulation time was set at 10 seconds. The duration of the fault was 4/60 sec. The fault was set to occur at 20/60 sec and be cleared at 24/60 seconds. The duration of the fault corresponds to the critical clearing time of the induction motor, estimated using equation (10). For under voltage protection of the induction motor, a circuit breaker is set to isolate the induction motor automatically when the bus voltages where less than 0.75pu.

B. *Results and Discusions*

The simulations were carried out and responses taken for the generator terminal voltage, Fig 4., the induction motor speed, Fig 5., mechanical power at the machine's shaft, Fig 6., the reactive power generated compared to that consumed by the induction motor load, Fig 7., and induction motor bus voltages, Fig 8.

i. The Generator Terminal Voltage

The results indicated that all PSS under investigation apart from FLPSS quickly recovered the terminal voltage of the Generator soon after the fault was cleared, with a settling time of about 2 sec on average.

ii. Induction Motor Speed

The results indicated that the FLPSS led to the stalling of the induction motor. All other PSS investigated restored the motor to normal shortly after the fault was cleared, after 1 sec.

iii. Mechanical Power at the machine's shaft

The results indicated that the FLPSS led to power system instability, while the other PSS investigated

iv. Induction Motor bus voltages

The results show the process of voltage collapse in the case of the FLPSS as the machine is unable to maintain constant voltage at its terminal.

v. Reactive power generated and reactive power consumed by the induction motor load

The results indicate that the FLPSS cause the machine to have a larger maximum overshoot in reactive power generation. The machine with the FLPSS is unable to meet the reactive power demand of the induction motor load and finally leads to voltage collapse of the system.

The active and reactive delivering capabilities of the generators have been lost by the FLPSS thus leading to the stalling of the induction motor load. This in turn led to the total voltage collapse as shown in Fig 8. and transient instability, Fig 6. This may be attributed to the fact that the high reactive power demand by induction motor loads, due to reduced voltages during the fault, caused the generators with the FLPSS to lose their ability to act as a constant voltage source. These resulted in the machines behaving like a voltage source behind the synchronous reactance, causing its terminal voltage to reduce. This in turn caused the induction motor load to demand more reactive power at the reduced voltages, which further lead to reduction in the load bus voltage, Fig 8. This finally resulted in a voltage collapse and the stalling of the induction motor.

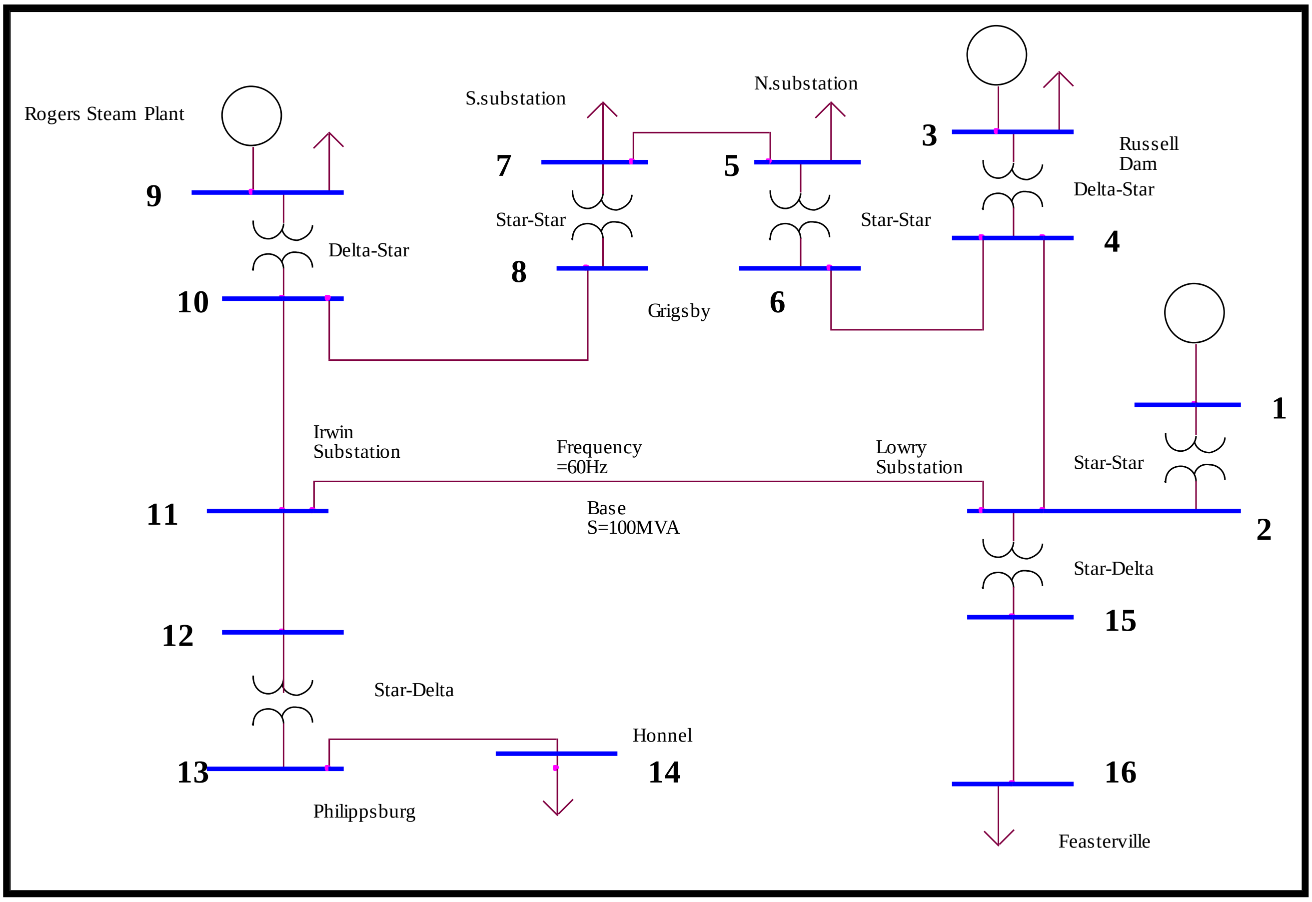

Figure 3 Single line diagram of the 16-bus model

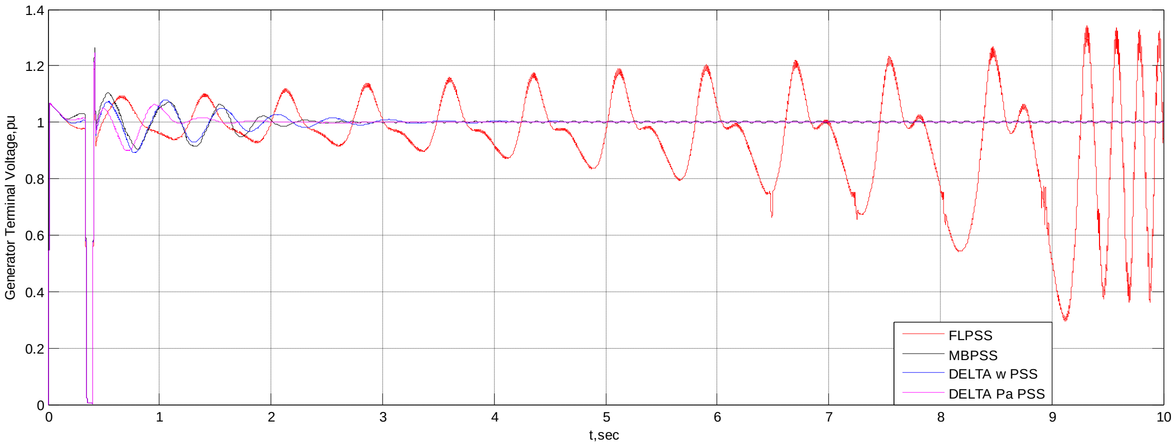

Figure 4 Generator Terminal Voltage Response

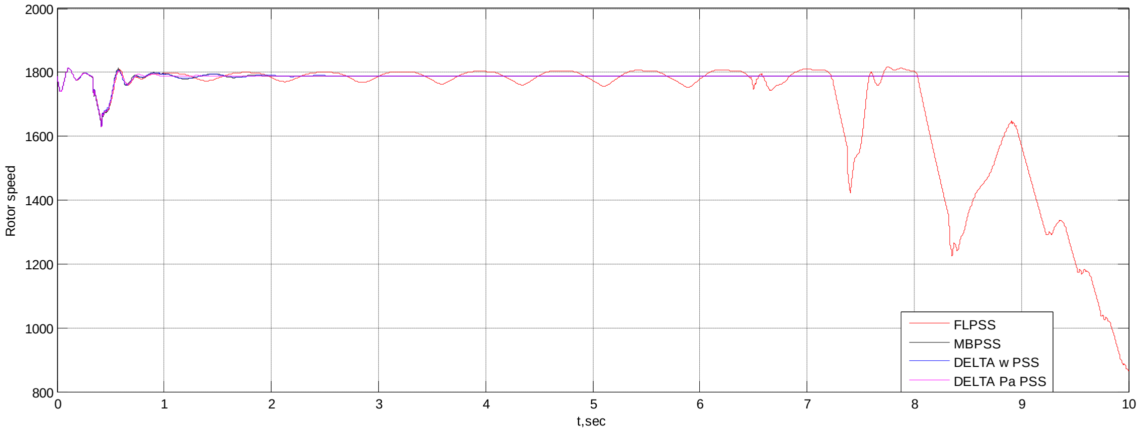

Figure 5 Induction Motor Speed Response

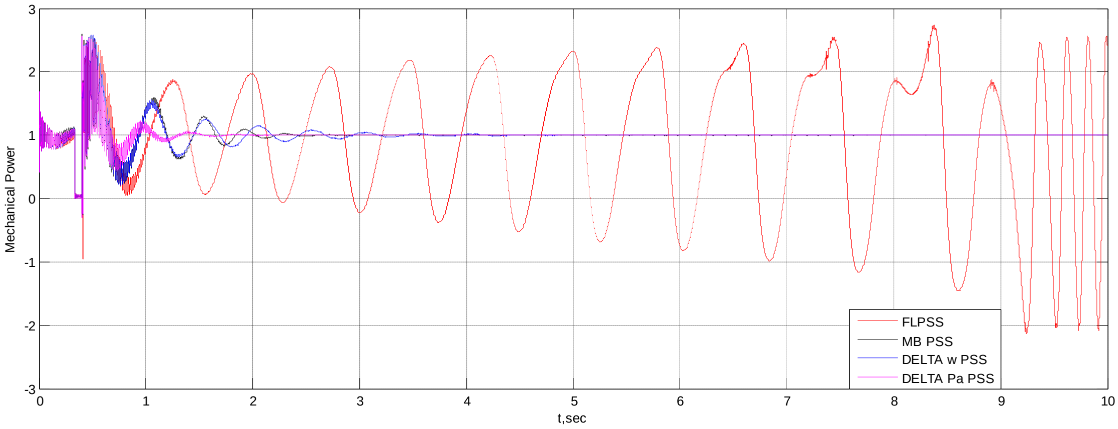

Figure 6 Mechanical Power at the Machine's Shaft

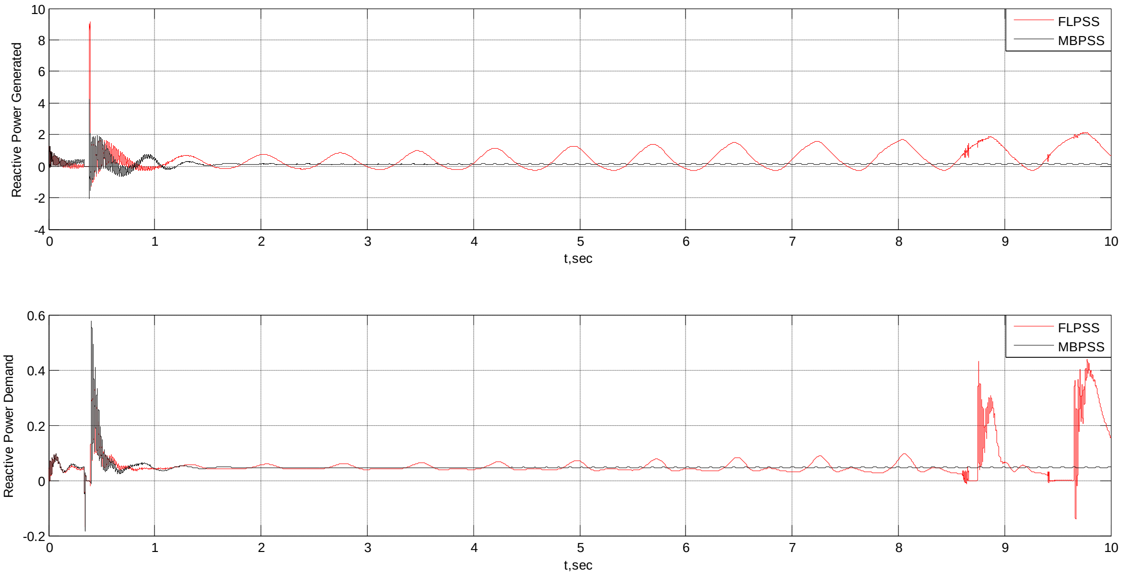

Figure 7 Reactive power generated and reactive power consumed by the induction motor load

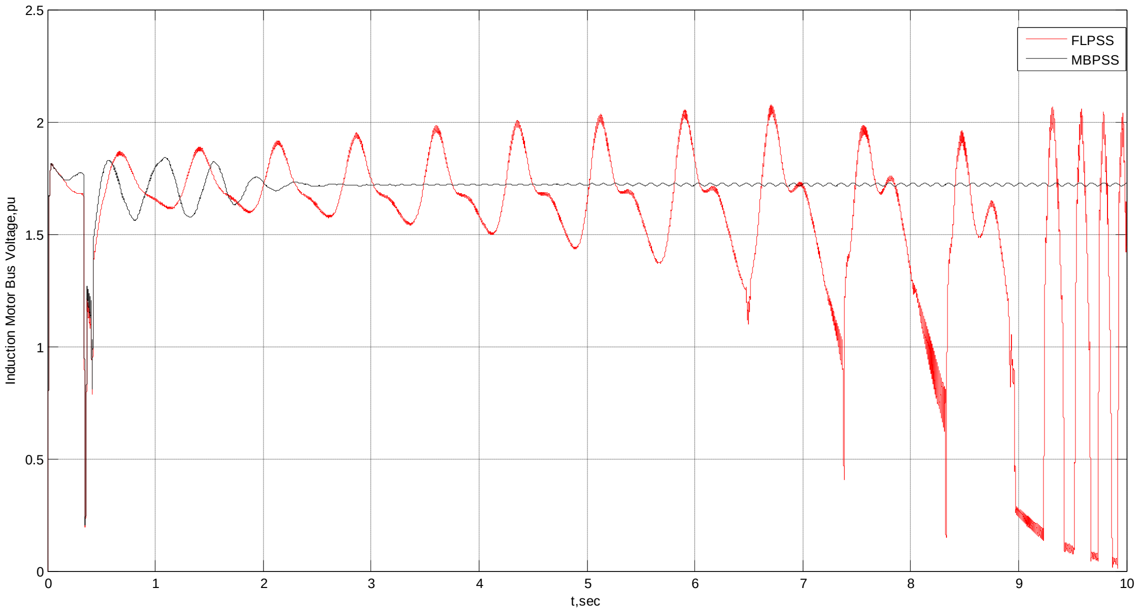

Figure 8 Induction Motor Bus Voltages

C. Conclusion

The effects of the excitation system have been shown to be very crucial in voltage stability studies. The speed of the AVR is of great interest in studying stability especially considering the high inductance in the generator field winding, which makes it difficult to make rapid changes in field current. This introduces a considerable lag in the control function.

The study proposes to re-evaluate the use of FLPSS for power system stability enhancement. There is need to research on the possibilities of a Hybrid PSS that captures the strengths of the FLPSS as outlined in literature, but also avoid the setbacks highlighted in this paper**.**

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