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Power System Dynamic Stability Improvement Using PSS Equipped with Microcontroller

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Abstract

In assessing the power system, the most important issue is the system behavior when the system is affected by a disturbance. In some plants in case a small event, oscillations are created that are not easily damped and this lack of damping causes the power plant shut down. So, conditions should be set such that the power plant damps the oscillations as soon as possible and returns it to the stable conditions. In this paper, microcontroller-based power system stabilizer (PSS) is designed that increases the single machine dynamic stability of the power system connected to an infinite bus by improving damping in the low frequency oscillation. The system stability is investigated by the eigenvalues and the results of dynamic simulations are provided in the time domain. Programmable interface controllers (PIC) have been used in designing digital PSS; then the continuous time domain PSS is converted to discrete time domain PSS and finally it is implemented on the microcontroller chip.

Keywords: Digital design, Eigenvalues, Microcontroller, Power system stabilize
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1. Introduction

Power system stability studies include the behavior of these systems in situations such as sudden changes in load or generation, transmission line fault, line out of the network, or sudden departure of one of the generator units [1,2].

In assessing the power system, the most important issue is the system behavior when the system is affected by a disturbance [3,4]. Small disturbances may cause oscillations in the domain that increases exponentially and leads to instability in the power system. Therefore to improve low-frequency oscillation damping system instability is improved by defining a stabilizing signal in the excitation system that this signal is taken from the power system stabilizer (PSS) [5,6]. Many studies have been carried out on various power system stabilizers (PSSs) [7,8]. Classical PSSs include pre-phase/post-phase networks to provide damping for low frequency oscillations [9,10]. Such stabilizers have attracted lots of attention due to simple structure and easy installation. There are various methods for setting the parameters of the classical stabilizer, such as frequency response techniques and state space design methods [11,12].

The stabilizers that are based on modern control theory design include optimal control, adaptive control, robust control, variable structure control, and intelligent control, the most common among which is the optimal control theory in large-scale systems [13,14]. Adaptive controllers are suitable for uncertain linear systems invariable with time. The objective function was developed as a Lyapunov function, and this function was based on fault detection, control effort, or closed loop error [15]. In the method of variable structure control, the system states are controlled using a control rule in a predetermined path and proceeded to the desired point with the dynamics determined by the designer. In the robust controller technique, the stability of the power plant is maintained with uncertain parameters, which can be power plant parameters, data input and output parameters, or transmission line parameters [16,17]. In general, this tool does not guarantee any damping for uncertain systems. In the

H∞ (H-infinity) optimization method, the stabilizer order is considered higher than of the power plant resulting in reduced system complexity and efficiency [18,19]. Intelligent control or efficient artificial intelligence includes high-speed and uncertainty and non-linear analysis. The techniques change their behavior in interacting with the power system [20]. Finally, the artificial neural networks are able to control power system under highly nonlinear domain of transient stability conditions [21]. A fuzzy logic-based stabilizer adjusts its parameters online according to the operation conditions and provides effective damping for a wide range of operation conditions [22]. Digital control systems can cover a wide range of control algorithms. The change in parameters and the implementation of a new strategy only needs to recompile a software program model, in which elements are variable unlike the analogy control system. So far, many studies are conducted on power system stabilizers but given recent developments in the power system and system complexity, there is a need to use a digital devise. Some of the advantages of digital systems are low cost and high computational velocity, easy implementation of sophisticated algorithms, the ability to communicate with computer systems and synchronization with remote control systems. For digital implementation the process of converting a continuous-time controller to a digital controller is needed so that the continuous-time and discrete-time states of the closed loop systems are matched [23].

The accuracy of these conversions is very important and has a direct effect on the final performance of the systems. In [24] are-design of optimal digital of the classic power system stabilizer (PSS) presented for single-machine power system based on optimal matching of the step response of both discrete time and continuous time systems. The analysis of digital control systems in a nonlinear manner is provided in [25] in which a power system with digital controllers is described as a hybrid dynamic system and then the stability analysis of power systems is investigated with an emphasis on digital PSS. In [26] has provided a new structured controller by plant input mapping (PIM) to achieve better results in terms of sustainability. Another technique of discretion is based on Taylor method and zero-order hold. This method has focused on the key properties of nonlinear systems such as balance properties and asymptotic stability [27].

PIM method is used in [28] for successful redesign of continuous time PSS. This method is one of discrete techniques to ensure the stability for any sampling rate and is well implemented for large sample intervals. Since the advantages of digital stabilizers are higher than the analogy stabilizers, in [29] the digital stabilizer implementation on microcontroller chip and power system stability is analysed.

In the present paper the stabilizer stability is addressed by the eigenvalues and electric torque and the stabilizer parameters are implemented based on the electrical loop transfer function and frequency response obtained from the system and then implemented on the Microcontroller chip by a digital redesign.

The dynamic study of the single-machine system connected to the shin is infinitely important because it is a small example of the behavior of the whole power system and provides the possibility of making decisions and providing comprehensive algorithms for the whole power system. In dynamic studies of single machine system, attempts are made to adjust the stabilization parameters of the power system for a dominant point in the system, where the damping of critical modes is maximum for that point, and a percentage of error is accepted for other working points. In fact, the power system stabilizer is installed on the generators to improve the dynamic status and stability of the small system signal. To study low frequency disturbances in the power system, a detailed and comprehensive model of the system will be needed that will show the dynamic behavior of the system, generator and its components well.

The major contributions of the present work can be summarized as follows:

1. The proposed PSS has a relatively simple structure and is suitable for real-time applications in future smart grids.
2. The serial capability of PIC microcontrollers with MATLAB software along with simulation is a graphic design tool in MATLAB, which helps to develop many simulation programs and control mechanical and electrical systems.
3. This paper is based on the assumption of local oscillating modes that other oscillating modes such as inter-zone, control and torsional modes can be considered in the design process.

The rest of this paper is organized as follows. In the section 2, power system dynamic model is presented and power system stabilizer design is described based on damping torque and Converting a continuous time transfer function to a discrete time transfer function and designing the digital stabilizer for power system is described in section 3. The MATLAB and microcontroller connection is established in section 4 and then the simulation results are presented in section 5.

2. Power System Model

Since the general system consists of synchronous generator subsystems, AC network, communication subsystems and static excitation subsystem, the element connection model has been used to connect these subsystems to each other. The single machine infinite bus power system is considered that the generator is equipped with an automatic voltage regulator and the governor and turbine dynamics are neglected. To increase generator rotor oscillation damping, the stabilizer creates electric torque component in phase with the rotor velocity deviation. So, the basic stabilizer functions add a stabilization signal to the system to compensate voltage fault oscillation of the excitation system along the transients or dynamic modes [30].

The linearized single-machine power system with power system stabilizer is presented in Fig. 1, where the stabilizer gain function states the damping rate introduced by PSS [31,32]. By adding a stabilization signal, the PSS compensates for voltage fluctuations in the excitation system during transient and dynamic states and creates an attenuation component in the phase by deviating the rotor speed of the machine [33].

Phase compensator block presents the suitable phase lead for phase lag between the exciter input and generator electric torque. The compensated phase characteristic is altered by changing system conditions and thus in addition to increasing torque and damping, results in increased synchronization torque. Wiper filter function acts like a high-pass filter and the wiper time constant T_W is usually between 1 to 20 seconds and it is long enough to pass stabilization signals without changing some frequencies. This function only allows the stabilizer to respond the changes quickly and prevents the constant changes in terminal voltage [34,35].

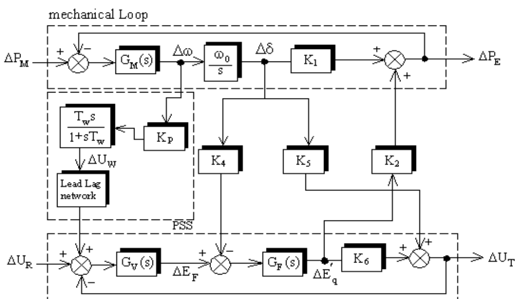


Fig. 1. Single-machine infinite-bus (Block diagram of SMIB system with PSS)

3. Digital Controller

There are two digital design methods for digital controllers: In the first method called direct digital design, the analogue power plant is discretized and then a digital controller is determined for the discretized plant. In the second method called digital redesign, an analogy controller is first designed for the analogue power plant and then there is digital redesign for the designed analogy controller. In the digital redesign method, an optimal matching is created between the step responses of the closed-loop of the continuous system and discretized system. In a closed loop control system, the timing response and the steady-state fault can be controlled [36].

In the present paper, the first step is to design a classical stabilizer. For digital implementation, the process required includes the conversion of a continuous time controller to a digital controller in such a way that continuous and discrete modes of the closed loop systems are consistent. The accuracy of the conversions is of great importance and has a direct impact on the system's final performance. The most common methods for discretize the continuous time controllers are Tustin and Hold Equivalence. The former is one of the most popular methods because of its simplicity and ease of use. In the present paper, a digital stabilizer was used to improve the stability of the power system. The fault signal in a power system is analogy. An analogy-to-digital converter is required for converting the fault signal into a computer-readable signal to use a digital controller. This process includes the periodic sampling of the input signal, and the samples are needed to be converted into a computer-readable digital code. Hence, the digital code is the beginning of the software implementation for coding. The converted signal was obtained using the digital-to-analogy converter. This conversion is done by the zero-order preserver transfer function [37]. Based on the recent developments in power systems and the complexity of these systems, designing the digital devices in the field has increased significantly. In a power system under disturbance, the use of these controllers is very useful due to smart operators. Today designing the control circuits can be performed with a simple microcontroller. Microcontrollers include a microprocessor, memory and input-output connections integrated in a single small chip. PIC serial microcontroller connectivity is one of several advantages of the microcontroller to be used for designing and implementing a power system stabilizer. PIC18F4520 microcontroller is used as a digital stabilizer [38] that is programmed by the high-level language C [39]. Digital redesign method is the process of converting a previously designed continuous-time controller to a suitable digital controller for digital implementation such that the continuous-time and discrete-time modes of closed-loop systems are compatible with each other. Fig. 2 shows a continuous-time analogy sensor. Analog sensors cannot be directly connected to the digital computer. The error signal in a digital control system is analogy and an analogy to digital converter (A/D) that converts the signal into a digital readable computer signal is used. Analog to digital conversion process is done by sampling the input signal periodically and converting these samples to a digital code is done by processing capability by a computer. Converting the computer digital signal to an analogy signal is done by a digital to analogy (D/A) converter. This conversion is done by the zero-order hold function. Analog to digital and digital to analogy converter circuits are made in many microcontrollers that each microcontroller can easily be connected to an analogy signal or power system [40]. So, in Fig. 2 it is possible to replace the digital parts by the microcontroller block.

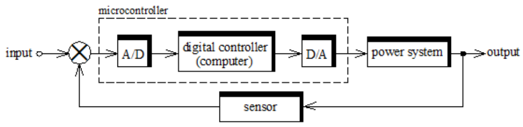


Fig. 2. Block diagram of microcontroller based digital control system

The designed continuous-time power system stabilizer is converted to discrete-time domain that is implementable on the microcontroller. Thus, rotor velocity deviation which is an analogy signal is obtained by A/D and then the output signal D/A has been introduced to the automatic voltage regulator (AVR). Tustin transformation is used to do the PSS transfer function conversions from the continuous to the discrete domain. PSS transfer function in continuous time includes [41]:

$$G_{PSS}(s) = K_{PSS}\left(\frac{sT_w}{1+sT_w}\right)\left(\frac{1+sT_1}{1+sT_2}\right) \quad (1)$$

By Tustin transformation the PSS open loop transfer function includes:

$$T_{PSS}(z) = K\frac{(b_1a_1)+(b_0a_1-b_1a_1)z^{-1}-b_0a_1}{(c_1a_2)+(c_0a_2+c_1a_0)z-c_0a_0} \quad (2)$$

where, a_0=T-2a, a_1=2a, b_0=T-2b, b_1=T+2b, c_0=T-2c, c_1=T+2c, a=T_w, b=T_1 and c=T_2. T is the sampling time. By substituting the PSS parameters designed in part II, the discrete-time transfer function of the stabilizer is obtained that is used in PSS performance loop after being converted to C code. The notable point is choosing the sampling time to match the continuous-time PSS frequency response with discrete-time PSS. The sampling time values are obtained based on $\omega_{\varphi m}$ which is zero frequency dB of the frequency response curve value for the analogy compensator [42]. So, with bode diagram plotting to determine zero frequency dB of the connection between PSS and the power system, the best sampling frequency is obtained based on the nearest digital PSS frequency response to the continuous-time PSS frequency response.

4. Matlab and Microcontroller Interface

The interface between MATLAB and microcontroller using a serial connection is done by computer serial port and TX and RX pins in the microcontroller. MAX232 chip is used to match the voltage level between the microcontroller and computer chips. Overall system block diagram is shown in Fig. 3. Micro pro for PIC software is used code the microcontroller by C language [43].

The advantage of this compiler is to create a library of commands with functions that can be applied in them. The work starts with the similar codes by microcontroller configuration PIC18F4520 and the micro specific function registry is used [44]. For communication between MATLAB and microcontroller via a serial port, there is a need to create a serial port in MATLAB and port specification are determined in accordance with specified microcontroller profile. MATLAB function has been rewritten as a functional block in the Simulink model that shows the digital PSS performance in power system. In MATLAB Simulink the time domain PSS acts by a zero-order hold block and MATLAB function block as digital PSS [45]. The reason for the presence of the hold is to rebuild the sampled signal in such a way that the resulting signal is very close to the signal before sampling.

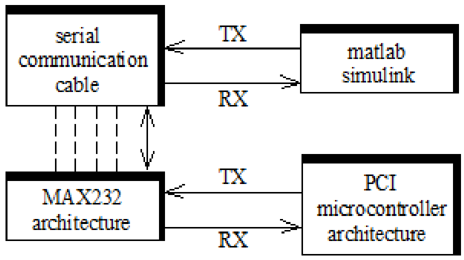


Fig. 3. Block diagram of MATLAB and microcontroller interface

5. SIMULATION RESULTS

Considering the single-machine power system, the transfer function $G_E(s)$ is as follows:

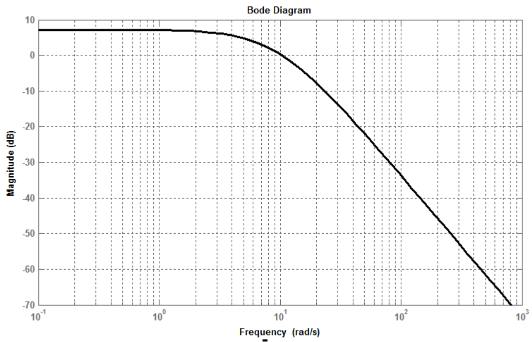
$$G_E(s) = \frac{18.9081}{0.0906s^2 + 1.8624s + 9.2360} \quad (3)$$

Figs. (4-a) and (4-b) present the bode diagram of the transfer function $G_E(s)$. As it can be observed the generator phase at a frequency of 9.54 rad/s is -90° that to obtain the maximum damping the compensator with the phase of 90° is required. Thus, the ratio of T_1 to T_2 is identified according to the Table 1. The value of K_{PSS} is obtained by considering the optimal damping and matrices A and B. The generator transfers function root locus and choosing compensator gain to obtain the desired damping is presented in Fig. (4-c). Root locus-based gain is selected such that the damping coefficient of the rotor model is maximized.

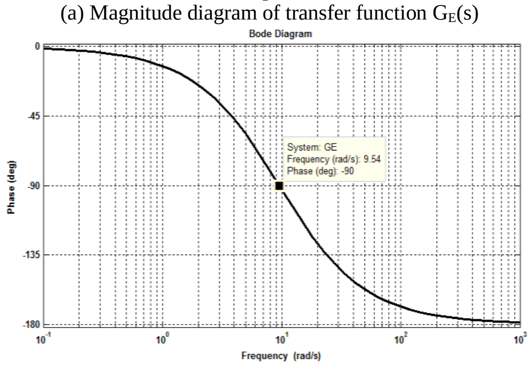
Gain in the instability border is 11.5 based on Fig. (4-c) that by setting the stabilizer at 3.83 the system gain goes to the stability. The stabilizer parameters are shown in Table 1.

Table 1
Values of parameters of power system stabilizers

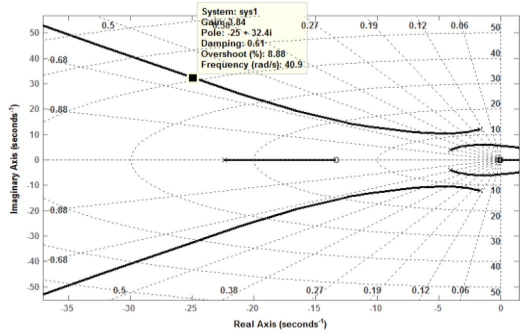
T_1	T_2	K_{pss}	T_w
0.75	0.075	3.83	10



(a) Magnitude diagram of transfer function $G_E(s)$



(b) Phase diagram of transfer function $G_E(s)$



(c) Showing gain compensation in accordance with the optimum damping

Fig. 4. Magnitude and phase diagram of transfer function and gain compensation

The system eigenvalues, damping coefficients and damping and synchronization torques at different operating points in the presence or absence of the stabilizer are obtained in Table 2.

As it can be observed the eigenvalues at instable operating points are transferred to the left part of the imaginary axis after applying the stabilizer and also the positive damping coefficients and damping and synchronization torques are increased. Time domain simulation with and without PSS in the unstable nominal operating point in Figs. (5-a) and (5-b) indicate the positive damping in response of PSS in response to rotor velocity deviation under the disturbance source ΔT_m and the Figs. (5-c) and (5-d) indicate positive damping at the presence of PSS in response to the rotor velocity deviation under the source ΔT_m.

The settling time of the rotor velocity response with PSS is much less than settling time of the rotor velocity response without PSS and the rotor stability is guaranteed. So, stabilizer transfer function in continuous-time domain includes:

$$G_{PSS}(s)=\frac{(27)s^2+(36)s}{(0.75)s^2+(10.075)s+1} \tag{4}$$

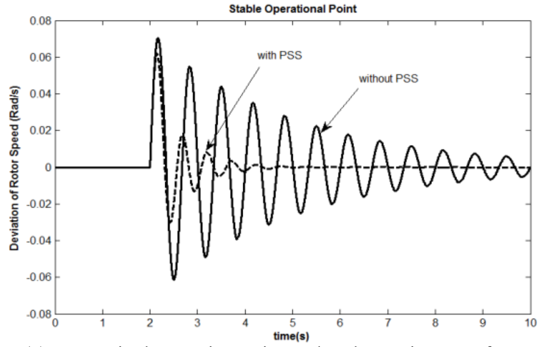
According to synchronous torque and Tustin transformation at discrete-time domain the digital stabilizer differential equation that is convertible to code C is obtained:

$$\begin{aligned} y[n] = {} & y[n-2]\left[\frac{T^2-20.15T+3}{T^2+20.15T+3}\right] \\ & - y[n-1]\left[\frac{2T^2-6}{T^2+20.15T+3}\right] \\ & + x[n]\left[\frac{3.6(30+20T)}{T^2+20.15T+3}\right] \\ & + x[n-1]\left[\frac{-216}{T^2+20.15T+3}\right] \\ & - x[n-2]\left[\frac{3.6(20T-30)}{T^2+20.15T+3}\right] \end{aligned} \tag{5}$$

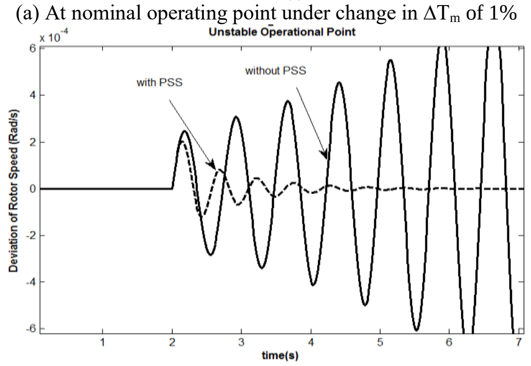
As mentioned before the sampling time T of the main key is the compliance between the digital and continuous time PSS. T is within the range of $0.15/\omega_\varphi$ to $0.5/\omega_\varphi$ where ω_φ is the zero-frequency dB of the frequency response size curves for analogy compensator.

Thus, the domain and phase curve are presented to present the zero-frequency dB of connecting the open-loop connection between PSS and power system SMIB in Figs. 6 and 7.

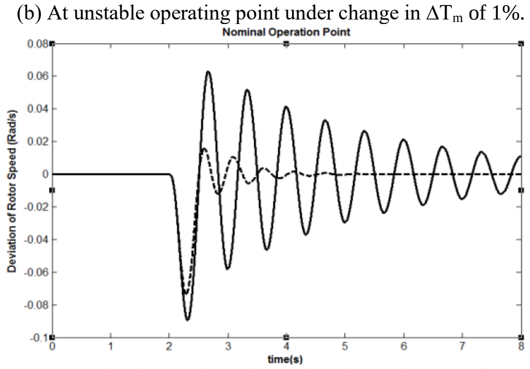
As it can be observed the zero-frequency dB in ω_φ is approximately equal to the amount of 78/8, rad/s. Therefore, sampling interval limit is within the range of T_{min}=0.0172 sec to T_{max}=0.0576 sec. Thus, the sampling frequency is within the range of 17.36 to 57.87 Hz. To choose the best sampling frequency the nearest digital PSS frequency response to the continuous-time PSS frequency response is considered.



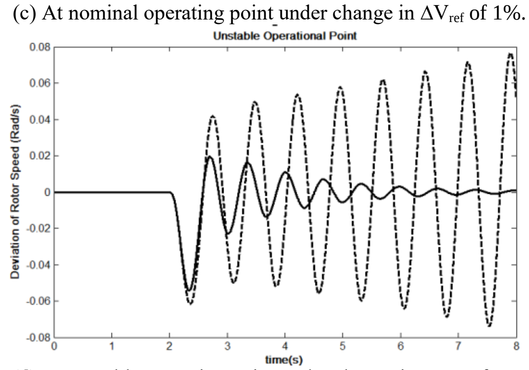
(a) At nominal operating point under change in ΔT_m of 1%



(b) At unstable operating point under change in ΔT_m of 1%.



(c) At nominal operating point under change in ΔV_{ref} of 1%.



(d) At unstable operating point under change in ΔV_{ref} of 1%.

Fig. 5. Rotor speed deviation response with and without PSS

Fig. 6 shows the effect of different sampling frequencies on digital PSS frequency response. Thus, digital PSS sampling frequency is selected as 55 Hz. In order to convert PSS transfer function to code C to be implemented in the microcontroller, the sampling time is considered as 0.01818 s.

Fig. 7 shows the digital PSS frequency response match with continuous-time PSS frequency in sampling time that confirms the designed digital PSS effectiveness. By substituting sampling frequency in (3) a differential equation (6) is obtained that based on the flowchart in Fig. 8 it is converted to code C and implemented on the microcontroller.

$$y[n] = (35.9679)x[n] - (64.1597)x[n-1] + (31.4857)x[n-2] + (1.7820)y[n-1] + (0.7824)y[n-2] \quad (6)$$

Using a serial connection, the connection between MATLAB and microcontroller has been established according the hardware in Fig. 9.

It is concluded that PSS response of the s domain has higher damping than digital PSS (microcontroller) the reason of which is time continuity that is normal. Therefore, it is attempted to define the most stability signal to the power system.

According to time domain simulations, digital PSS has stabilized the power system in instable performing point. It is concluded from the Fig. 10 the designed PSS equipped with microcontroller in different operating points is resistant.

In addition, there is a high level of agreement between digital PSS compared to continuous time PSS in response to the rotor velocity deviation of power system SMIB. Fig. 11 presents an image of the digital PSS hardware designed based on microcontroller and the interface within the workstation.

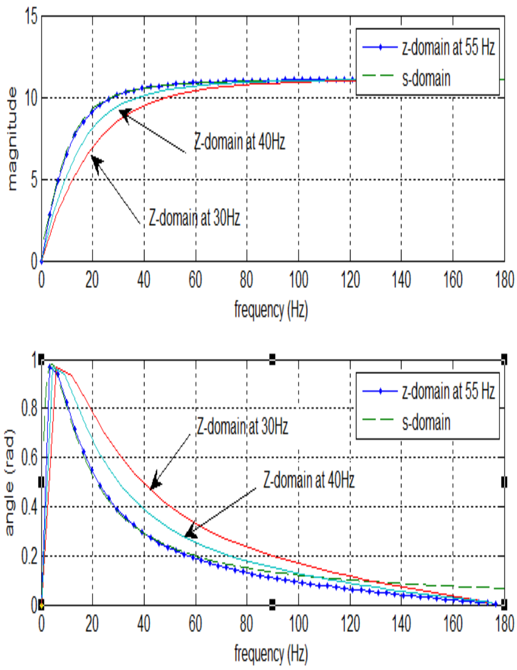


Fig. 6. Frequency response, effect of sampling frequency on the frequency response of the digital PSS

Table 2.
Eigenvalues and torque damping and torque synchronization of SMIB system

	Without PSS		***With PSS***	
	Nominal operating point	***Unstable operating point***	***Nominal operating point***	***Unstable operating point***
P	136	112	136	112
Q	83.2	-32	83.2	-32
λ_1	-12.9507	-17.3355	-22.3414	-21.0756
$\lambda_{2,3}$	-0.33±j9.42	0.2604±j8.4500	-1.6829j12.075	-0.409±j9.21
λ_4	-6.9315	-3.737	-4.0889±j3.908	-7.2586
λ_5	-	-	--	-4.7316
λ_6	-	-	-0.1002	-0.1001
Ξ	0.0355	-0.0308	0.1380	0.0444
K_s	1.3418	1.0788	1.8423	2.3967
K_D	3.1744	2.4675	7.6924	4.9525

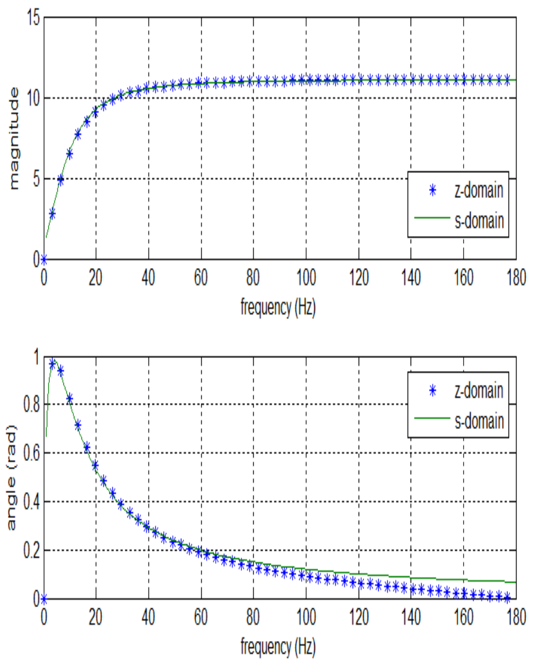


Fig. 7. Frequency response, comparison between the frequency response of the designed digital PSS and the response of the continues domain PSS

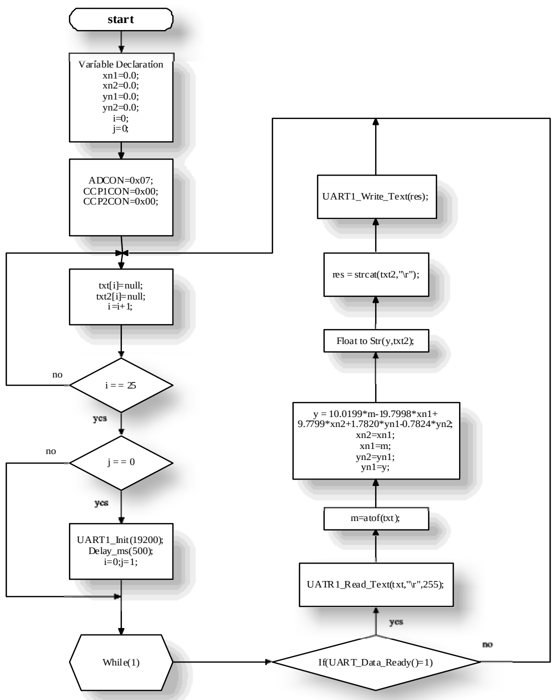


Fig. 8. Microcontroller C-code flowchart

6. Conclusion

In this paper, microcontroller-based PSS is designed in which the continuous-time PSS is converted to digital PSS by Tustin transformation method. MATLAB Simulink model developed by the power system with microcontroller is studied via a serial connection. Microcontroller equipped stabilizer is applied on the power system and the effectiveness of this stabilizer is presented on increasing the power system stability under different operating points with a time domain simulation.

Simulation results indicate that the designed PSS in addition to match with the continuous time PSS, increases system stability under different operating points and this presents the effect of the designed digital PSS. By carefully modeling the components of the power system, and using a digital stabilizer, the small signal stability of the system can be improved. However, the damping rate of oscillating modes in the digital system is less than the continuous time system. This is natural due to the continuity of time in continuous time control systems.

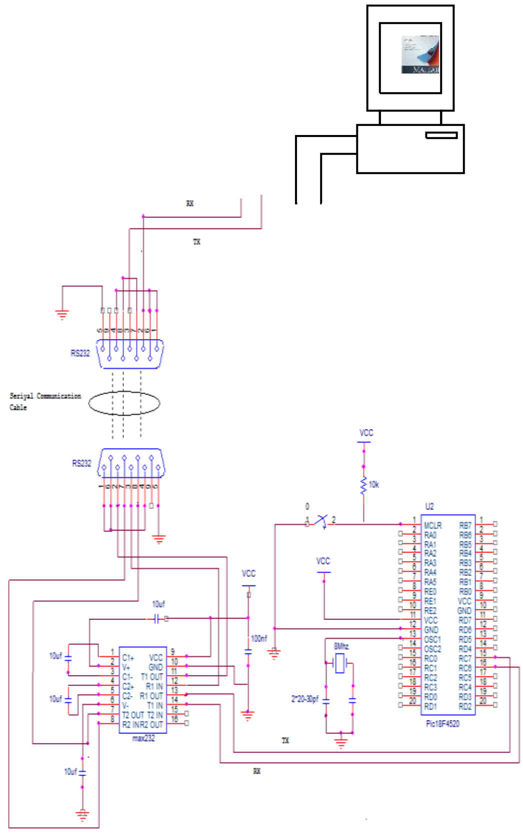
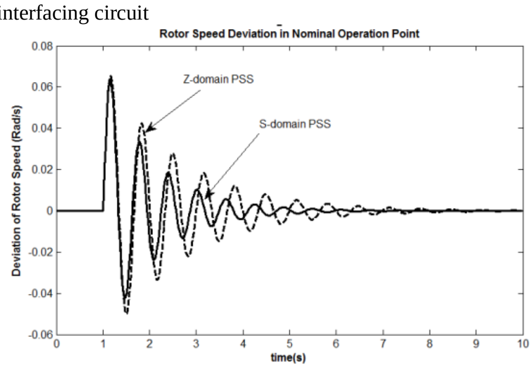
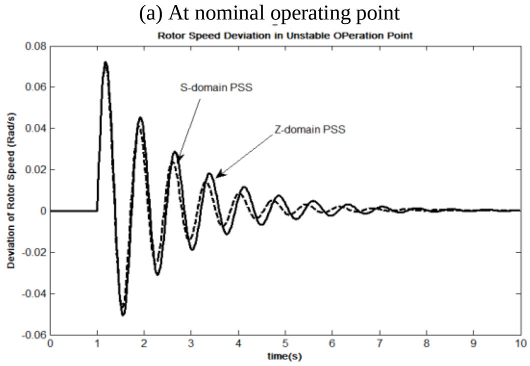


Fig. 9. MATLAB and PIC18F4520 microcontroller interfacing circuit



(a) At nominal operating point



(b) At unstable operating point

Fig. 10. Rotor speed deviation response comparison of digital PSS and continuous domain PSS under change in ΔTm of 1%.

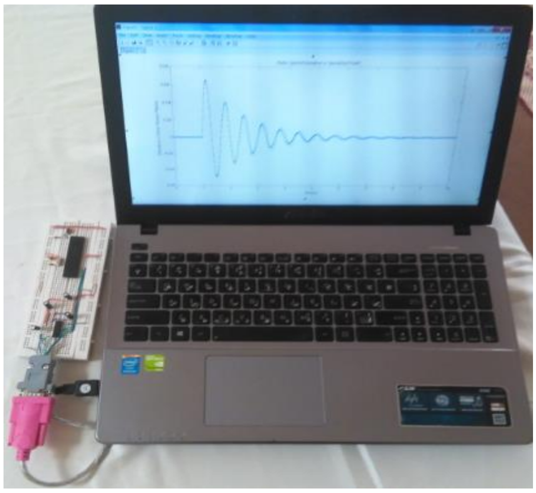


Fig. 11. The microcontroller based digital PSS hardware with MATLAB Simulink interface

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