Resonant Control for Synchronous Machine Damping

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Synchronous machine is an undamped oscillator and electrical damping is essential to keep the synchronous machine synchronised with the grid. An oscillation damping control architecture known as a classical power system stabiliser is used extensively in the power industry. The classical power system stabiliser is a narrow bandwidth lead compensator that reacts to small-signal oscillations only. The project proposes an alternative two-pronged approach to system stability by introducing a new methodology for Automatic Voltage Regulation design and a new architecture for Power System Stabiliser. The alternative Power System Stabiliser is called a resonant controller. The resonant controller targets the desired resonant frequency with closed loop feedback. This is useful for the Power System Stabiliser application because it can provide feedback at the resonant frequency, controlling electrical torque and hence angular displacement. Unlike the existing classical Power System Stabiliser, the resonant controller can be designed independent of the Automatic Voltage Regulation design. Relieving the consequential requirement to redesign the Power System Stabiliser with changes to Automatic Voltage Regulation design. The proposed methodology for Automatic Voltage Regulation design enables a Proportional Integral Differential style lead-lag controller to be designed to meet specific design criteria. In the project a 2.5 second settling time was achieved, which is required by the Australian Energy Marker Operator. Meeting specific design criteria is difficult with the existing heuristic approach to tuning an Automatic Voltage Regulation. The proposed Automatic Voltage Regulation methodology relieves the need to place the system in undesirable operating conditions for tuning. In a simulated environment, the project successfully designs and implements the resonant controller Power System Stabiliser and the lead-lag controller Automatic Voltage Regulation. Comparison between the proposed resonant controller Power System Stabiliser and the existing classical Power System Stabiliser, demonstrates that the resonant controller is capable of decreasing oscillations around the operating point by 11.06dB in the project, without effecting the whole frequency spectrum which occurs with a classical Power System Stabiliser. This reduces noise feedback that can introduce oscillations into the grid, therefore allowing more Network Service Providers to have Power System Stabiliser incorporated into their system.

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I. Introduction

In Australia, the National Energy Market (NEM), similar to the majority of power systems worldwide, consists predominately of large thermal power stations that utilise synchronous generators to produce electrical power. [1]. The NEM is managed by the Australian Energy Market Operator (AEMO), who ensure adequate system strength by ensuring a minimum number of synchronous machines are kept online at any one time. The system strength is the ability of the power system to recover from disturbances and comes from large synchronous machines rotated by a prime mover connected to hydro, gas or coal turbines. The minimum requirement of synchronous machines comes from the fact that non-synchronous generators, such as batteries, solar or wind do not readily have this natural characteristic. AEMO have invested interest in the quality of the NEM and do not allow Network Service Providers (NSP) to inject excessive power oscillations into the grid.

Under normal operating conditions all synchronous generators rotate at a constant angular speed, and therefore the difference between rotor angles of connected generators will be constant [2]. This is considered the equilibrium condition or steady state. However, when subject to a disturbance, the angular speed of the synchronous machines will diverge from the steady state condition because of the discrepancy between mechanical torque and electrical torque and subsequently their associated powers. This will cause a change in rotor angles. If the rotor angle differences settle at a steady state, not necessarily at the same angular difference, then the synchronous machines are considered to be stable or synchronised. Conversely, if the rotor angle differences increase open-endedly, then the synchronous machines have lost synchronism. Likewise, if the rotor angle differences don’t settle within an adequate time, the synchronous machines are considered not to be adequately damped and pose a risk of becoming unstable and would cause a machine to trip protection devices and isolate the machine from the power system.

The swing equation of the synchronous machine is shown at Eq. (1) [2], which shows how the angular displacement of the rotor is related to the accelerating power \( P_a \), responsible for returning the rotor back to equilibrium. The synchronous machine draws analogously to a non-linear undamped mass-spring equation. Where the rotor displacement \( \delta \) (load angle) determines the amount of accelerating power \( P_a \), to return the rotor to steady-state. Provided by the difference in mechanical power \( P_m \) and electrical power \( P_e \). Notice that no damping is accountant for in the swing equation that describes the mechanical behaviour of a synchronous machine, therefore to prevent oscillations, damping needs to be supplemented. Damping of these oscillations is the aim of the project.

\[
\frac{2H \omega_a}{\omega_a} \frac{d^2 \delta}{dt^2} = P_a = P_m - P_e
\]  

(1)

For the swing equation Eq. (1) \( H \) is the inertia constant and \( \omega_a \) is the synchronous angular frequency of the synchronous machine. The electrical torque \( (T_e \omega_a) \) related to electrical power \( P_e = T_e \omega_a \) is comprised of two parts; synchronising torque, intrinsic to synchronous generators and damping torque. The lack of either causes the system to become unstable. If there is a lack of synchronising torque, the rotor angle increases progressively. If there is a lack of damping torque, the rotor will oscillate with growing amplitude which is a characteristic problem of synchronous machines because there is no inherent mechanical damping in interconnected systems. Adding to the problem of an underdamped machine is the negative effect that Automatic Voltage Regulation (AVR) has on the damping torque. In the pursuit to increase synchronising torque and control the transient response of the voltage, necessitated by an AVR, comes at the cost of steady state stability [3]. Employing a power system stabiliser (PSS) enhances these torques and thus provides increased rotor angle stability, ultimately increasing power stability [2].

Interchange of power and angular position of rotors is a significant aspect of power system stability [3]. The relationship is non-linear, refer to Eq. (2). The torque versus angle, refer to Fig. 2 illustrates that the power varies as a sine function of the angle. When the angle is zero, no power is transferred. The power transferred increases up to a maximum at which point the angle is 90 degrees, then power decreases after this point with an increase in

Nomenclature

AFM = Atomic Force Microscopy  
AEMO= Australian Energy Market Operator  
AVR = Automatic Voltage Regulation  
NER = National Energy Regulations  
NSP = Network Service Provider  
PID = Proportional Integral Differential  
PSS = Power System Stabiliser  
SMIB = Single-Machine Infinite Bus
angle. Referring to Fig. 1 and Eq. (1), notice that $\delta_1$ is a stable equilibrium, that is torque is restorative, whereas, $\delta_2$ is an unstable equilibrium, that is torque enhances the disturbances.

$$ P_o = \frac{E'_d V_o \sin \delta}{x'_d} \tag{2} $$

Where; $P_o$ is the output power, $E'_d$ is the transient open circuit voltage, $V_o$ is the infinite bus voltage, $\delta$ is the load angle, and $x'_d$ is the transient d-axis reactance.

As described, synchronous power transfer is non-linear, however, it is more convenient to utilise linear models to characterise the system to perform steady state analysis. A linear model coupled with frequency analysis will enable controllers to be readily designed. The linearisation process in the context of synchronous machines will be described latter in the linearisation section of the report.

Many architectures and techniques already exist for controller design to dampen oscillations, however the project’s aim is to introduce a new controller architecture for PSS and a new design technique for AVR, to satisfy the shortcomings of the existing controllers when attempting to solve the electro-magnetic oscillation problem for synchronous machines. The proposed controllers are expected to solve the existing shortcomings associated with existing controllers and is discussed in the following paragraphs. The proposed resonant controller is expected to satisfy the requirements, as the problem is well defined and the synchronous machine application exhibits oscillations at a distinct resonant frequency that could be reduced with a resonant controller. The resonant controller is proven in the application of Fast Atomic Force Microscopy, refer [4], where mechanical vibrations were damped with repeatable success. Although the application is unrelated to synchronous machines, the technical risk is reduced for proposing the resonant controller in the new application of synchronous machines, because the underlying control theory in both applications is related.

Existing classical controllers used extensively in the power industry for AVR and PSS are cross coupled. The PSS design depends on the AVR and it cannot be designed independently. That is, classical controller design architecture and methodology lacks the ability to be designed independently from each other. This cross coupling is problematic, when the AVR is required to be changed, then the PSS consequently needs to be redesigned.

Another problem with classical PSS, is that the classical PSS effects the whole frequency spectrum, which is undesirable. The is undesirable because the controller is feeding back a large gain across the whole spectrum and therefore has the ability to feedback unwanted signals (noise) that can lead to oscillations.

Traditionally PSS is usually only approved for implementation by the AEMO for NSP that operate larger synchronous machines, compared to other connected synchronous machines on the same grid. The NSP proposing their synchronous machine power generation need to provide solid evidence that their PSS is robust and satisfies operating conditions [5]. The reason why larger synchronous machines are usually granted permission to use a PSS, is that larger synchronous machines inherently have a greater level of inertia and are less susceptible to shifting their operating frequency and synchronise with other synchronous machines. This is important for PSS design, because PSS are tuned for the current synchronous machines oscillations. If the operating point of the synchronous machine shifts, the designed PSS may affect other synchronous machines. Furthermore, become ineffective for the local synchronous machine. AEMO do not allow NSP to inject excessive power oscillations into the grid. Therefore, AEMO stance is; better to not have a PSS controller introduced that maybe uncertain attached to synchronous machines, therefore avoid risking a PSS that could potentially do harm to the grid. For this reason, currently with the existing PSS controllers, not every NSP has the opportunity to have an operating PSS incorporated into their system.

Adding to the current problem of existing controllers, the classical PSS requires knowledge of the transfer function between the electrical torque output and reference voltage input of the synchronous machine. This transfer function is not always available or known. In this case, the design of the classical PSS is not possible. An alternative to the classical PSS architecture could solve these problems, which is the aim of the project.
II. Synchronous Machine Model

A. Linearising and the SMIB model

Synchronous machines are used in the power grid and have non-linear operating conditions. Typical grids have multiple generators and thousands of buses, which creates a complex problem for the analysis of transient stability [3]. The complexity can be reduced by Linearising the non-linear equations that describe the synchronous machine about an operating point and limiting the model to just one generator, connected to a theoretical infinite bus that represents the grid. The simplifications are justified for finding the correct solution to the more complex problem, as the solution is well behaved in the frequency domain for both the simplified model and real-world situation [3]. The theoretical Single Machine Infinite Bus (SMIB) schematic is shown at Fig. 2 [6]. In the schematic, the synchronous machine analysed is represented by $E_q \angle \delta$, the infinite bus (the grid) is represented by $V_{\infty} \angle \theta$, and the interconnected transmission line is represented by the reactance of $jX_L$. The model is a convenient way of analysing transient synchronous machine behaviour of a complex real-world multi-machine system. The frequency responses and associated resonant peak, obtained from the SMIB, vary insignificantly in the multi-machine system and therefore the methods utilised to design controllers with the SMIB transfer over to the practical multi-machine system. If a linearised model solution is found to be stable, then too, the non-linear system solution will also be stable.

The synchronous machine for a SMIB system can be described mathematically for transient stability by Eq. (3), (4) and (5). The mechanical dynamics are modelled using a second-order equation and the Resistive-Inductive (RL) field coil is modelled using a first-order equation.

$$\dot{\delta} = \omega_0 \omega - \omega_0$$

$$\dot{\omega} = \frac{1}{2H} (P_m - E_q'q + (x_d' - x_q')I_d q)$$

$$\dot{E_q}' = \frac{1}{\tau_{do}} (E_{fd} - E_q' - (x_d - x_d')I_d)$$

The non-linear differential Eq. (3), (4) and (5) [6] are combined with the set of non-linear algebraic equations for SMIB at Eq. (6) [6]. Then the non-linear Eq. (3), (4) and (5) are linearised about an operating point of $\delta^0$, $\omega_0$ and $E_q^{0}$. The reason that these equations are non-linear is because electrical power is proportional to the sine of the power angle $\delta$. This linearisation process produces a state space representation, refer Eq. (7) [6] and the set of K Parameters, refer Eq. (8) [6].

$$\frac{\Delta \omega}{\Delta \delta} = \begin{bmatrix} \frac{K_p}{2H} & -\frac{K_p}{2H} & 0 & 0 & 0 & 0 \\ \frac{K_p}{2H} & \frac{K_p}{2H} & 0 & 0 & 0 & 0 \\ 0 & \frac{K_pK_q}{T_s} & \frac{K_pK_q}{T_s} & 0 & 0 & 0 \\ 0 & \frac{K_pK_q}{T_s} & \frac{K_pK_q}{T_s} & 0 & 0 & 0 \\ \frac{1}{\tau_{do}} & \frac{1}{\tau_{do}} & \frac{1}{\tau_{do}} & \frac{1}{\tau_{do}} & \frac{1}{\tau_{do}} & \frac{1}{\tau_{do}} \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \frac{\Delta \omega}{\Delta \delta} \quad (7)$$

$$K_1^1 = \frac{E_{q'}^0 V_{\infty} \cos \theta^0}{x_d' + x_c}$$

$$K_2^1 = \frac{E_{q'}^0 V_{\infty} \sin \theta^0}{x_d' + x_c}$$

$$K_3^1 = \frac{x_d' + x_c}{x_d' + x_c}$$

$$T_s = \tau_{do} K_1^1, \quad K_1 = \frac{x_d' - x_d}{x_d' + x_c} V_{\infty} \sin \theta^0$$

Once the linear model described by Eq. (7) and (8) of a synchronous machine is obtained, numerical values can be entered into these equations. The eigenvalues of the ‘A’ Matrix for the state space representation, refer to Eq. (7), can be used to find the resonant frequency of the synchronous machine. Also, transfer functions can be obtained, by taking the Laplace of the state space representation, refer to Eq. (7), and relating the output to the input, enables the analysis of transient studies and subsequent design of stability controllers.

The two relevant transfer functions that result are found at Eq. (9) and (10), being the load angle/field voltage transfer function and the terminal voltage/field voltage transfer function, respectively. The terminal voltage/field voltage transfer function will prove significant for the design of the AVR. Whereas, the load angle/field voltage transfer function will prove significant for the design of the PSS.

$$\frac{\Delta \delta(s)}{\Delta E_{fd}(s)} = \frac{-K_p K_q}{(1 + s T_s)(2H^2 + K_p K_q + K_1 K_q) - K_p K_q K_q}$$

$$\frac{\Delta V(t)}{\Delta E_{fd}(s)} = \frac{K_p K_q}{(1 + s T_s)(2H^2 + K_p K_q + K_1 K_q) - K_p K_q K_q}$$

Whilst the analysis is structured on small signal linear model and the practical application is non-linear, it is expected that if the linearised model solution is found to be stable, then too, the non-linear practical application solution will be stable, which was Henri Poincaré’s contribution to the field of differential equations [7].
B. Assumptions of the Heffron-Phillips model

To enable acceptable results with appropriate simplifications, the following assumptions were made by adopting the Heffron-Phillips model, refer to Fig. 3 [8] for a synchronous machine. These assumptions were considered acceptable, because the model is used and proven extensively in the power industry for frequency analysis, and the model accounts for the dominant poles. Therefore, if more complex components were to be introduced in the model, they would have an insignificant effect on the solution. These are the model assumptions:

- The model used is a Single Machine Infinite Bus model that only exists for understanding of operating principles and convenient for transient analysis. Practically, this model is extended out to multi-machine systems. The difference will be explored in the multi-machine section of this report.
- Line resistance, \( r_e \), equals zero. This allows the air gap power, considered equivalent to terminal power. Using the per unit system, means that air gap power is considered equivalent to air gap torque.
- No amortisseur windings (damper windings). This simplifies the inductance modelling equations.
- The governor action, \( T_m \) (mechanical torque) is neglected and remains constant. Therefore; \( T_m \) equals zero.
- The various components that contribute to inertia constant and damping factor of the mechanical characteristics of the synchronous machine are combined into variables \( H \) and \( K_D \), respectively.

In reality, the dynamics are more complex than the accepted model, however increasing the complexity of the model does not yield any significant deviation from using the simplified model.

C. AVR and PSS

The standards of power generation plant performance are categorised by the National Energy Regulations (NER) Rules with the following ‘acceptable levels’ that met a certain level of technical requirements:

- The ‘minimum access standard’ is the minimum technical level of performance permitted [5].
- The ‘automatic access standard’ is the highest technical level of performance required to be proven for unopposed acceptance [5]. A Generator is not required to prove capability more than the applicable automatic access standard [5].
- A ‘negotiated access standard’ is a level of performance, which is between minimum access standard and automatic access standard relevant to the technical requirement [5]. Negotiated access standards must be agreed with the connecting NSP and the AEMO [5]. The negotiated access standard should be close as reasonably practicable to the automatic access standard for demonstrating generator technical performance [5].

The purpose of the AVR, refer to Fig. 3 for location within SMIB model, is to regulate the terminal voltage of the synchronous machine. When the system is subject to a disturbance, the AVR decreases voltage settling time and ensures zero steady state error, whilst providing transient stability. By increasing the bandwidth of the frequency response, the rise time can be reduced. As rise time is inversely proportional to bandwidth. Reduced rise time will create a faster response that will provide additional synchronising torque [2].

The purpose of the PSS, refer to Fig. 3 for location within SMIB model, is to provide additional damping of rotor oscillations. The following are important aspects of PSS:

- The damping factor, \( K_D \), that is characteristic of a synchronous machine is typically too small. Thus, gives rise to the need to supplement the mechanical oscillations, that is, damping generator rotor angle swings.
• The role of the PSS is an increased steady state stability, as oppose to AVR’s role of transient stability.
• A method utilised to damp the mechanical oscillations in an appropriate time (as opposed to slow response from the governor), is to alter the applied electrical torque, \( T_e \), proportionally to the change in machine speed. This can be achieved by inputting a signal to the AVR to change the input electrical torque, proportionally to the picked-off change in angular velocity [6].
• Gain at high frequency needs to be minimised in order to reduce the noise amplification through the PSS.
• The phase margin needs to be set at the local mode frequency to avoid destabilising intra-plant mode with high frequencies.
• A PSS tuned for high response can result in shaft damage. This occurs particularly at light generator loads when the inherent mechanical torque is small. [3]
• There exists a trade-off between improving damping and affecting synchronising torque, which leads to instability [3].

D. Resonant controllers
The resonant controller architecture has been proven in an unrelated application and is expected to work in the new application of electro-mechanical damping of synchronous machines [4]. The reason why it is expected to work, is that, although the applications are unrelated, the underlying resonant dynamics are similar. The controller successfully damped mechanical oscillation in the field of Fast Atomic Force Microscopy (AFM) [4]. The advantage of the resonant controller compared to other damping controllers, is the simple methodology and ease of implementation, which is desirable in the power industry. A resonant controller with an integral block had been interfaced to x-axis and y-axis of the Piezoelectric Tube Scanner (PTS), to increase the functioning speed of the AFM for high speed imaging. This had the effect of improving the tracking performance by damping the resonant mode of the scanner [4]. The ability of the resonant controller to dampen vibrations, is expected to transfer successfully over to the new application of synchronous machine rotor oscillation damping.

III. Work Completed - AVR design and resonant controller
The proposed architecture for AVR and PSS allows for independent design and tuning. Thus, the report will discuss these designs separately. First the design of the AVR and then the design of the PSS.

A. Design and implementation of Automatic Voltage Regulator
The AVR implemented is a Proportional Integral Differential (PID) controller, this ensures overall robust transient behaviour including fast rise time, minimal overshoot and zero steady-state error. By designing the AVR as a Lead-Lag Controller enables a systematic methodology to satisfy specific design requirements and ensures that an optimum solution can be obtained. Whereas, using other traditional methods to design the PID, such as the Ziegler-Nichols method [6], requires putting the system into what may be an unacceptable level of oscillation to tune the PID parameters. These types of tuning methods are heuristic, and as such require trial and error and do not guarantee an optimal solution. By matching the coefficients, the designed controller can be converted to the identifiable general form of a PID controller, for the purposes of comparing other tuning methods.

The AVR design control goals and justifications were:
• The closed-loop system is to have zero steady-state error for a unit step reference input.
• A crossover frequency 60 rad/s. Increasing the bandwidth results in a faster rise time.
• A minimum of 60º phase margin. Provides additional damping, to reduce overshoot and oscillations.

The AVR design process followed:
Select the value of the constant gain block, the bode plot is observed, before the controller is added for the gain at 60 radians, for the project example, was found to be -32dB. This means that a constant gain of +32dB is needed, equivalent to a linear value of 40 for the constant gain block [6,10].

The Lag block provides an integrator, which ensures the required zero steady-state error with step-reference input is obtained. This is accomplished with a lag block of \( \frac{1+\frac{\omega_2}{\omega_1}}{s} \). By selecting a value of \( \alpha \) to be 1/60, ensures that the block does not cause any lag at the desired crossover frequency.

The Lead block is designed by analysing the phase at the crossover frequency of 60 rad/s. The phase is approximately 1 degree, at this frequency, therefore 59 degrees below the required 60 degrees. Therefore, the \( \phi_1 \) value is 59.

\[ m = \frac{1+\sin(\phi_1)}{1-\sin(\phi_1)} = \frac{1+\sin(59)}{1-\sin(59)} = 13.00 \]

\[ \omega_2 = \frac{\omega_1}{\sqrt{m}} = \frac{60}{\sqrt{13.00}} = 16.64 \]

Therefore; \( \omega_2 = 16.64 \)

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\[ \omega_p = m \times \omega_2 = 13.00 \times 16.64 = 216.31 \] Therefore; \( \omega_p = 216.31 \)

The AVR controller implemented as a lead-lag controller is built from separate controller blocks, refer to Eq. (11). First block is the constant gain, \( K \). Second block is the lag block. Third block is the lead block.

\[
C(s) = K \left( \frac{1 + \frac{s}{\alpha}}{s} \right) \left( \frac{1 + \frac{s}{\omega_2}}{1 + \frac{s}{\omega_p}} \right) \result \quad C(s) = 40 \left( \frac{1 + \frac{s}{60}}{s} \right) \left( \frac{1 + \frac{s}{16.64}}{1 + \frac{s}{216.31}} \right)
\]

With the AVR controller designed and added to the SMIB system, a step input increase of 0.05pu (per unit) was applied to the system and the settling time measured. Refer to Fig. 4, the 5% settling time was measured to be 2.332 seconds. The settling time requirements are discussed in the following section. The aim is to just meet the requirement and not exceed by a lot, to avoid the negative consequences associated with AVR gain and the reduction in damping torque.

B. AVR comparison against industry standards

**Steady State.**

The Australian Energy Market Commission (AEMC) make and amend the National Electricity Rules (NER). Chapter 5 Part B of NER provides a framework for connection and access to a transmission network or a distribution network and to the national grid. [5]. Chapter 5 Part C of NER addresses the network related issues following the negotiation of a connection agreement under Part B, namely the design of connected equipment, inspection and testing, commissioning and disconnection and reconnection. Section 5 of Chapter 5 details the 10% settling time requirements for a 5% \((1.00\text{pu} \text{ to } 1.05\text{pu voltage})\) step input, refer below for a summary [5].

- When unit not synchronised; less than 2.5 seconds settling time for 5% step (1.05pu) voltage [5].
- When unit synchronised and no limiting device; less than 5 seconds settling time for 5% step voltage [5].
- When unit synchronised, limiting device; less than 7.5 seconds settling time for 5% step (1.05pu) voltage [5].

Adding the designed AVR controller to the SMIB system and subjected to a 5% step input, achieves 10% settling time of 2.332 seconds. Which is within the required 2.5 seconds, being the most stringent requirement, that pertains to a unit not synchronised. Therefore, the designed AVR is a suitable controller for the application in terms of the ability to achieve settling time requirements.

Conversely, there is a limitation as too how quick the system should respond. Caused by the conflicting problem; by increasing the gain of the AVR, and thus assisting transient (early swing) stability, comes at the cost of increasing oscillatory action (damping) [9]. Also, responding too quickly has risk associated with breaking mechanical components. Additionally, the model does not account for such quick response dynamics and could have unforeseen consequences. This problem can be avoided by limiting the gain provided by the AVR to alleviate undamped oscillations. However, this approach alone is not suitable when transmitting via long transmission lines and thus the damping needs to be supplemented with a power system stabiliser [9].

**Damping requirements**

The 5 second halving time damping criteria specified by the National Electricity Rule (NER), covers the associated small-signal stability range of oscillation frequencies from 0.314rad/s (0.05Hz) to 3.770 rad/s (0.60Hz) [5] applicable to the project’s scope. Achieving at least this damping criterion meets the ‘minimum access standard’ and is easy to observe the competence visually, compared to the equivalent damping coefficient requirement of \( \sigma = -0.139 \) Nepers per second [5] (where \( \sigma = \zeta \omega_n \)). However, the damping coefficient can be calculated by first calculating the damping ratio (\( \zeta \)) and the undamped natural frequency (\( \omega_n \)), with known
parameters. The undamped natural frequency and the damping ratio, refer to Eq. (12) and Eq. (13), respectively, are found by using the state-space representation to obtain the characteristic equation. Where; \( \omega_n \) is the undamped natural frequency, \( K_1 \) is the synchronising torque coefficient, \( \omega_o \) is the rated speed in elec. H is the inertia constant, \( \zeta \) is the damping ratio, \( K_D \) is the damping torque coefficient. If an exact damping solution is required, use the damping coefficient method. Alternatively, if efficiency is advantageous over accuracy, then use the 5 second halving time method, which is particularly suitable for initial tuning.

\[
\omega_n = \sqrt{\frac{K_1 \omega_o^2}{2H}} \quad (12)
\]

\[
\zeta = \frac{1}{2H\omega_o} \quad (13)
\]

C. Design and implementation of PSS

The initial step of designing the PSS controller, is to obtain a bode frequency response of the SMIB linear model with the AVR. To obtain a bode, a single transfer function from the entire system with AVR, Fig 5, must be obtained between \( \Delta \delta \) and \( \Delta V_{\text{ref}} \). A single transfer function can be completed either manually by control block reduction theory, or with the MATLAB and Simulink. Due to the complexity of the model, using MATLAB and Simulink to verify calculations is recommended, to avoid any possible errors and efficiency of recalculation if parameters are altered.

![Figure 5. SMIB system with AVR.](image)

Figure 5. SMIB system with AVR.

![Figure 6. Single transfer function (\( \Delta \delta / \Delta V_{\text{ref}} \)) for SMIB system with AVR.](image)

Figure 6. Single transfer function (\( \Delta \delta / \Delta V_{\text{ref}} \)) for SMIB system with AVR.

The transfer function for the entire SMIB system with an AVR, refer Fig. 6, is used to obtain the frequency response shown at Fig. 7. The frequency response shows a peak at 4.66 rad/s, caused by a pair of complex poles [11]. This peak is the resonant frequency of the example synchronous machine and is the focus of the project. That is, the PSS controller needs to attenuate this peak. The resonant controller will be designed to target this frequency to reduce the peak and achieve a larger bandwidth for a flat frequency response. This peak is the frequency deviation around the operating point. Theoretically, if the synchronous machine exhibited absolutely no damping, this peak would have infinite magnitude.

D. PSS resonant controller

PSS can use a variety of signals to provide feedback to dampen the electro-mechanical oscillations. Alternatives include change in: field current, armature current, accelerating power [3]. For the project, the change in angular speed \( \Delta \omega \) was selected for feedback due to simplicity and proven track record in the power industry [3]. This signal provides positive speed feedback to provide electrical damping torque. Therefore, controlling the oscillations by supplementing the accelerating torque.
The aim of the project is to design and implement a Power System Stabiliser (PSS) in the form of a resonant controller. The benefit of using a resonant controller for the PSS application, is that the resonant controller targets the peak magnitude that is characteristic of the frequency response associated with synchronous machines. Whereas, other traditional PSS, effect the whole frequency spectrum. For the damping application that a PSS provides it is undesirable to alter the resonant frequency, but only provide damping at the existing resonant frequency. This approach avoids feedback signals due to unmodeled dynamics that could lead to oscillations.

The transfer function of the resonant controller used is shown at Eq. (14).

\[
PSS \text{ resonant controller TF} = \frac{-g_\omega C_R s(R_R + L_R s)}{L_R C_R s^2 + R_R C_R s + 1}
\]  

The procedure used to design the PSS resonant controller is as follows: The resonant controller needs to be tuned to the system resonant frequency, shown by the peak of Figure 6, which is 4.66 rad/s. Tuning to the resonant frequency is achieved by selecting the appropriate values of \(L_R\) and \(C_R\) with Eq. (15) so that \(\omega_r\) (measured in radians) is equivalent to or near the resonant frequency of the combined system. Best practice, for finer tuning, is to vary either \(L_R\) or \(C_R\) and keep the other constant. This method uses Eq. (15) and results in the resonant frequency being able to be altered in a more predictable way, which assists efficient tuning. For the project, \(L_R\) was set to 1 and \(C_R\) changed for tuning to the resonant frequency of 4.66 rad/s. Rearranging to find the resonant frequency and letting \(L_R = 1\), this becomes equation (16). The gain was set to \(g_\omega = -70\) to provide the necessary level of feedback for the example.

\[
\omega_r = \frac{1}{\sqrt{L_R C_R}} \quad (15)
\]

\[
C_R = \left(\frac{1}{\omega_r}\right)^2 \quad (16)
\]

Summary of example PSS resonant controller parameters were: \(g_\omega = -70\), \(L_R = 1\), \(C_R = \frac{1}{64}\), \(R_R = 40\), \(\omega_r = 4.66\).

The value of damping resistor, \(R_R\) is initially set arbitrarily and tuned after observing the frequency response. If the damping resistor \(R_R\) is not set to an appropriate value, it might cause unwanted phase shift in the closed-loop response of the system. That is, choosing too smaller of a value of \(R_R\) creates a notch in the frequency response near the resonant frequency, reducing system performance and stability. Likewise, choosing too large of a value of \(R_R\), results in the system not having enough damping. Therefore, there exists a balance for selecting an optimum damping resistor value. For the project, this balance was found with a damping resistor value of 70. Note that because the project is implementing the resonant controller with a software-based transfer function, there does not exist the limitation that would pertain to a physical representation of the controller. For example, \(E\)-series resistors.

With the PSS design complete, it was added to the SMIB and AVR system. The new frequency response obtained at Fig. 8 shows that with the addition of the PSS resonant controller, the peak was targeted and attenuated by 11.06dB. Thus, providing a flatter response for a greater bandwidth increase by 1.61 rad/s. The frequency response changed as expected, due to the pair of complex poles now having a greater damping ratio, \(\zeta\) [11]. The greater the damping, the more that the response will flatten out in the magnitude and rotate at the phase [11].

![Figure 8. System with AVR and PSS. Peak attenuation of 11.06dB.](image)
With the resonant controller PSS added to the system, the time domain response was obtained refer Fig. 9. This shows that the system when subject to a disturbance, causes the load angle $\delta$ to change and settle to a new value. Notice that the blue oscillations decay around the red ideal transition curve. This indicates that the system with the introduced resonant controller PSS is stable for a 5% voltage step. Also, notice in Fig. 9 how the change in load angle $\delta$ is negative for a positive increase in voltage, which occurs at the same time. This is due to the preservation of power, referring to Eq. (2), as voltage drives up load angle drives down.

E. Resonant controller PSS comparison with Classical controller PSS

The classical PSS was designed and implemented for the purposes of comparing against the proposed PSS resonant controller. The architecture of the classical PSS is shown at Fig. 10 [12].

$$G_{PV}(s) = \frac{K_A K_3 (3+sT_R)}{(1+sT_R)(1+sT_3)+K_A K_3 K_6} \quad (17)$$

Where $K_A$ is the transfer function of the AVR. Here lies the problem with the classical PSS. This embedded AVR transfer function (represented here as $K_A$) creates the dependency and unwanted cross coupling of the PSS to the AVR. Select parameters for the lead compensator that will exactly offset the measured phase. Using traditional lead compensator theory, split the phase requirements equally over two blocks, refer Fig 10, if needed due to large phase offset requirements.

The frequency responses at Fig. 12, shows the comparison between the system before PSS, after adding resonant controller PSS, and after adding classical PSS. Notice the increased bandwidth achieved by the resonant controller PSS compared to the classical PSS.
The classical PSS requires that the transfer function between change in electrical torque and change in reference voltage to be known, not always possible in a practical setting. However, resonant controller PSS design does not require this transfer function. The classical PSS architecture is dependent on AVR design, this requirement is alleviated with resonant controller AVR. The classical PSS effects the whole bandwidth and could introduce noise and oscillations. Whereas, the resonant controller PSS targets the necessary frequency band only.

IV. Future Work

A. Multi-machines

The SMIB is a theoretical approach to understanding a complex system. The real world multi-machine system would have a frequency response that only slightly varies the peak location along the frequency spectrum. As the resonant controller is capable of handling peak variations, therefore makes it an ideal controller to meet the needs of real world complex multi-machine systems. That is, the resonant controller is a robust design, well suited to the industry application of synchronous machine dampening.

The frequency response characteristics are essentially the same for multi-machines. Modal analysis is performed for the multi-machine system in the frequency domain to identify dominant poles [2,13]. The generator that possess the dominate pole should have the PSS applied to its excitation system. The design of the damping should be based off the dominate generator, so that if a fault occurs, instability is avoided [13]. The resonant frequency of a multi-machine system is expected to shift from a single machine, however only slightly and not enough to be missed by a well-designed notch attenuator of the PSS resonate controller.

V. Conclusion

The synchronous machine was described as an undamped oscillator and electrical damping was shown to be essential to keep the synchronous machine synchronised with the grid. An oscillation damping control architecture known as a classical power system stabiliser used extensively in the power industry, was shown to react to small-signal oscillations only. The simulation demonstrated how an alternative power system stabiliser called a resonant controller, provides superior damping in the synchronous machine application. The resonant controller design, tuning method and implementation was demonstrated. The comparison between the proposed resonant PSS controller and the existing classical PSS controller showed that the proposed controller is superior to the classical controller to improve oscillation damping of synchronous machines and highlighted the benefits of the method used to realise the design. The lead-lag controller methodology shown for the design of the AVR proved that the controller can be designed to meet certain design goals, without needing to rely on heuristic design methodology. Advantageous to satisfy AEMO requirements and alleviate the need to stress the system in undesired operating conditions for AVR tuning.

References

[18] IEEE Standard 421.5-2005