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A Survey on Coordinated Design of Automatic Voltage Regulator and Power System Stabilizer

Hêmin Golpîra, Hassan Bevrani, Ali Hessami Naghshbandy

Abstract – *A power system must be capable to regain its stability and desired performance following any change of operating point. To meet satisfactory voltage regulation and damping performance on a wide range of operating conditions, the designed automatic voltage regulators (AVR) and power system stabilizers (PSS) must be enough robust, by working in a coordinated manner. This paper presents an overview of the key issues and new challenges on coordinated AVR-PSS design in interconnected power systems. A brief survey on the recent developments is presented, and new challenges imposed by introducing renewable energy sources (RESs) are emphasized.*

Keywords: *AVR, Coordination, PSS, Renewable Energy Source, Robustness*

Nomenclature

K_{PSS}	PSS gain
T_w	Washout time constant
T_1, T_2	Lead-Lag time constants
K_1	Synchronizing torque
D	Damping torque
K_{A1}	Synchronizing torque by AVR
D_A	Damping torque by AVR
K_{P1}	Synchronizing torque by PSS
D_P	Damping torque by PSS
A, B, C	Constant matrix
ξ	Damping ratio
n	Total number of dominant eigenvalues in linearized model
$\alpha(.)$	Additive white Gaussian system noise (state excitation noise)
$\beta(.)$	Measurement noise
x_i	State variables vector
w_i	Disturbance and area interface vector
u_i	Control input vector
z_i	Controlled output vector
y_i	Measured output vector
X, P	Symmetric and positive-definite matrices
V_t	Terminal voltage
P_e	Electrical power
P_m	Mechanical input power
P_a	$P_m - P_e$ (Accelerating power)
V_{set}	Voltage reference set point
V_{err}	$V_t - V_{set}$ (Voltage error signal)
$\Delta\omega$	Rotor speed variation
$\Delta\delta$	Rotor angle variation
I_d	Direct current component
I_q	Quadratic current component
V_d	Direct voltage component
V_q	Quadratic voltage component
R_c	Positive definite symmetric matrix which weights the energy of the control
$K(t)$	Kalman gain of the associated Kalman filter
α_1, α_2	Positive coefficients which can be chosen according to different sensitivity requirement of power frequency and voltage.
Q_c	Non-negative definite symmetric matrix which weights the variations of the state around its nominal value

I. Introduction

Satisfactory performance of power system can be achieved by maintaining the generator terminal voltage at a constant value [1]. In other word, voltage regulation plays an important role in power system security. Thus, voltage regulators (VRs) were added to generation units to keep the terminal voltage at a fixed value. By technology development, conventional VRs are replaced by fast responding automatic voltage regulators (AVRs).

The AVRs cause stable operation of power system when it encounters with sever disturbances. Therefore, the AVRs improve the transient stability and keeps terminal voltage at a preset value. However, installed fast responding AVRs deteriorate small signal stability by introducing electromechanical modes in power system [2]-[5].

Continuously load/generation changes and various

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disturbances conduct power system to operate in wide range of operating points which introduce low frequency oscillations (LFOs) [6]-[8]. When an electromechanical oscillation occurred in power system, the torque resolved into two components, one in phase with machine rotor angle (synchronizing torque) and other in phase with machine rotor speed (damping torque).

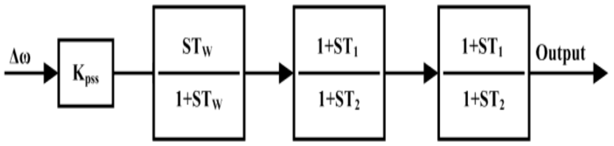


Fig. 1. Power system stabilizer structure

Lack of synchronizing/damping torque or both of them result in system instability. Before widespread use of AVRs in power system, instability mainly occurred due to the lack of synchronizing torque. This type of instability was manifested in the form of aperiodic drift of rotor angle of synchronous machines. Installed AVRs in generation units compensate lack of synchronizing torque in power system. Other types of instability resulted in the lack of damping torque as sustained or increased oscillations of rotor angles [10].

Regarding to the above states, the AVRs affect performance of power system by improving transient stability and decreasing small signal stability.

The AVRs improve transient stability by increasing the synchronizing torque, i.e. increasing synchronous power between interconnected generators, while decrease damping torque which result in rotor oscillations [9].

Economic reasons and environmental constraints led the system to operate transmission lines at maximum transfer power capacity. On the other hand, the small magnitude and LFOs may limit the ability of transfer power [2], [4].

A supplementary controller, namely power system stabilizers (PSSs), is added to power system to eliminate LFOs.

The PSSs are employed to produce an auxiliary damping torque. In other word, the PSSs modulate the generator terminal voltage and thereby extend stability limits [2]. A PSS usually consist of two phase-lead compensator, a washout filter and a constant gain as shown in the Fig. 1.

The phase-lag between exciter input and electrical torque is compensated by means of phase-lead compensators. The PSSs do not react by the steady speed changes. Therefore, a high pass filter, namely washout filter, is employed to eliminate DC signals [11], [12]. The rotor of steam generator turbine made up several pieces with different masses which connected to each other by the coupling devices through shaft. When the operating point changes, in addition to the LFOs, torsional oscillations are occurred between these sections.

Low damped torsional oscillations beside interaction of power system controllers cause to the sustained or increased oscillations in the system [13]. Thus, some torsional filters are required to remove torsional oscillation when the input signal is speed/frequency variation. However, in analysis of power system dynamics the steam generator-turbine rotor is assumed as a single mass and therefore, torsional oscillations can be neglected.

The first use of PSS was reported in early 1960's on hydraulic plants on the Moose which used rotor speed variation (Δω) as input [11]. However, detrimental effects on the torsional oscillations limited application of this type of PSS on thermal power plants. Therefore, to solve this problem a new type of PSS which used combination of speed and electrical power variations as its input was introduced [12]-[16].

The AVRs and PSSs produce torques in phase with rotor angle variations and speed variations, respectively. However, both AVR and PSS employ field voltage to produce these torques which are not in phase. In other word, a control signal is applied to generator to satisfy two conflict control action. Hence, an enhancement in one may cause deterioration of the other. Therefore, a tradeoff between these control actions is required.

The impact of AVR and PSS on the power system stability has been shown in the Figs. 2. In this figure, the torques resolved into damping and synchronizing components.

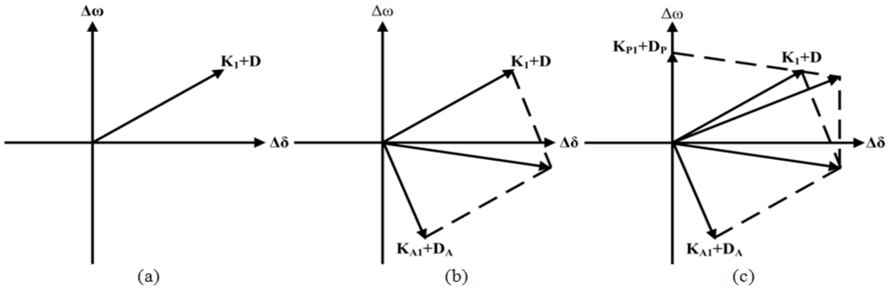
The system is stable when these components have the positive values. In Fig. 2(a) impact of constant excitation without PSS and AVR on the power system is depicted. It clarifies that the system is operating in stable condition. Adding AVR to system inject an extra torque with positive synchronizing and large negative damping component to the system which result in total negative damping torque (Fig. 2(b)).

Lack of damping torque component in this condition makes the system unstable (oscillatory instability). Applying a torque which is in phase with rotor speed variation compensates the lack of damping torque and conduct the system to stable condition (Fig. 2(c)). The PSSs are employed in power system to produce this torque.

The PSSs are installed in power system to eliminate the LFOs which have detrimental effect on power system operation. Numerous oscillation modes exist in power system based on the size of units.

Cancelling all of modes in a power system is neither practical nor economical. However, there are two modes of concern, namely local mode and inter-area mode. Local mode appears in the frequency range of 0.8 to 2.0 Hz and occurred when generators in a plant swing against rest of the power system.

The inter-area mode is occurred when two groups of generators in different area swinging against each other. The frequencies of this type of oscillations are in the range of 0.1 to 0.7 Hz [11], [17], [18]. The PSSs are usually designed to damp oscillations of modes in power system.



Figs. 2. Impact of AVR and PSS on the power system stability; a) constant excitation b) constant excitation +AVR and c) constant excitation+ AVR+PSS

The main issue in using of these controllers, AVR and PSS, is how to tune the controller parameters. In general, PSS philosophy relies on the phase compensation. Phase compensation is a control strategy based on linear control theory. For a power system with non-linear equations, tuning of PSS parameters is done when the equations are linearized around the operating point. Therefore, the performance of the PSS severely depends on the operating point [18], and the PSS parameters are tuned to have a good performance at the nominal operating point. However, various disturbances, load changes and faults excurse the operating point from nominal one. Thus, the controller performances are deteriorated by these changes [7], [17], [18].

Several approaches for tuning of power system stabilizer parameters are introduced in [10, 19-31]. Most of these papers introduced methods which ensured satisfactory performance of power system in a wide range of operating points. However, all of these studies considered the system with conventional AVR-PSS structure. The conventional AVR-PSS firstly was introduced in the most celebrated paper in power system dynamics by DeMello and Concordia [10]. In this way, two separate stages are considered. First AVR parameters are tuned to achieve acceptable transient stability then, the PSS is designed to meet the required damping [6, 34, 35]. Most of these papers used cancellation approach to extend the small signal stability region. These researches do not take into account the physical constraints which imposed to the PSS. In other word, in some operating points large phase compensation is needed which cause PSS saturation. Another fact that was neglected in these works is neglecting the conflict between AVR and PSS. Thus, a trade-off must be done between dynamic and transient stability which is not considered in these papers. Furthermore, several simplified assumptions in these papers degrade the performance of controllers in practice [35], [36].

To overcome the above challenges, a new methodology was introduced for tuning AVR and PSS parameters in [6], [9], [37]-[46]. New methodology employs robust control design strategies to meet required criteria in a wide range of operating points. The control design strategy is applied to the combination of AVR and PSS to obtain a robust AVR-PSS. In other word, AVR and PSS must be co-ordinated to provide trade-off between the two conflict requirements at any condition [36].

In the last two decades, some studies have considered an integrated design approach to AVR and PSS design using domain partitioning [37], robust pole placement [38], and adaptive control [39]. Moreover, several control methods have recently been made to co-ordinate the various requirements for stabilization and voltage regulation within one new control structure [6], [9], [40]-[46]. This paper considers these new control structures and explains their advantages and disadvantages.

II. A Survey on the Recent Developments

The recently published papers in the field of coordinated AVR and PSS can be classified into five categories.

1. The control strategy based on identification techniques
2. The control strategies based on switching concept
3. The control strategies based on fuzzy concepts and intelligent techniques
4. The control strategies based on optimization methods
5. The control strategies based on robust control approaches

The introduced methods in [9], [35], [36] for designing robust controllers belong to the first category. The first one relies on the process identification. Thus, the main problem which affects application of this method is complexity of model identification. In other word, for a large system such as power system with a high dimension, time varying and non-linearity properties, model identification is impractical or difficult. The control strategies of this category are briefly discussed at below and some of their advantages and disadvantages are demonstrated.

K. T. Law et al. [35], [36] considered an ideal AVR and PSS in analyzing AVR-PSS coordination. A technique of modern robust control namely, internal model control (IMC) was employed to design a robust controller.

The IMC firstly introduced by Garcia & Morari in 1982 [45]. The IMC theory states that control can be achieved only if the control system encapsulates some representation of the process to be controlled. In this method, process output is predicted by using the process model. If the model be perfect, control strategy becomes open-loop as shown in the Fig. 3.

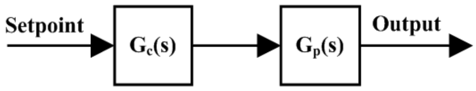


Fig. 3. Open-loop control strategy

In the Fig. 3, controller $G_c(s)$ is used to control process $G_p(s)$. By assuming the $G_E(s)$ as the exact representation of process, ($G_p(s)$), the perfect control is achieved by considering:

$$G_c(s) = G_E^{-1}(s) \quad (1)$$

Equation (1) clarify that for any condition, the output is equal to the set-point. A high level performance of IMC is achieved when the open-loop processes be stable. In practice, often the model is imperfect (model-process mismatch) and the open-loop process is not stable. Hence, first the process becomes stable by using conventional feedback as shown in the Fig. 4. In other word, robust controller is obtained by properly modifying the difference. Thus, the process is first pre-stabilized and then the conventional IMC is applied to obtain a robust controller [46], [47]. The simple structure and parametric design of the controller make it attractive for electric power industry. Furthermore, the closed loop structure of proposed method is used to compensate the phase-lag between the input and output signal. Thus, structure of PSS became simpler by eliminating the phase-lead compensators. In addition to the complexity of model identification, another disadvantage of this method is considering AVR and PSS as ideal elements. Therefore, some of real constraints and numerous unknown parameters and uncertainties are neglected. These made the method far from practice and it is not implementable in practice.

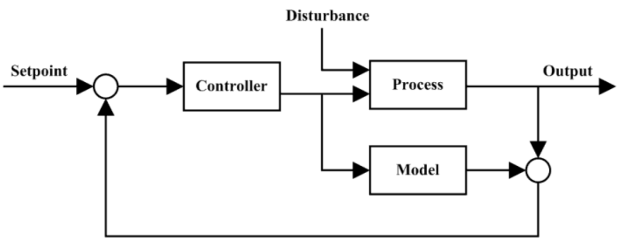


Fig. 4. Modified IMC structure

Trade-off between AVR and PSS are provided in [9] by using predictive control. The model predictive control (MPC), implement complete process model to control the future behavior of the plant [48], [49]. The method uses two axis model of synchronous generator to employ additional control signal. The current and voltage components are required to compute the field voltage which is required to satisfy the voltage regulation and small signal stability [9], [50]. Satisfactory performance of controller i.e. voltage regulation and small signal stability is achieved by selecting a control law. This control law is described as:

$$\frac{dV_t}{dt} + K\frac{dP_e}{dt} = K_v V_{err} + K_p P_a \quad (2)$$

where K, K_v, K_p are the coefficients which are specified based on terminal voltage condition, direct and quadratic voltage and current components in steady state. These parameters determine rate of oscillations damping and voltage recovery. By changing operating point, these parameters are also updated to get their satisfactory performance. From the measured I_d, I_q, and V_d, the V_q which is needed to satisfy the required performances will be obtained [9]. The disadvantages which are associated with this method are as follow:

1- Predictive control is an appropriate algorithm for systems with large time constant. In analyzing of small signal stability, the phenomena are occurred in small range of time. Therefore, the predictive control probably, does not have a satisfactory result for power system.
2- The time-variancy and non-linearity inherent of power systems reduce the efficiency of predictive control method.
3- Designed control structure based on this method is complex and not useful practically in power system applications.

The second category consists of the method introduced in [41], [42]. This category selects switching strategy to provide a trade-off between two conflict requirements of dynamic performance of power system. For a specified fault a unique switching time is obtained based on trial and error method.

Wang et al. [41] assumed the line reactance and infinite bus voltage as a constant value, and therefore used direct feedback linearization (DFL) to design robust controller to regulate voltage and improve transient stability. Feedback linearization is an approach in nonlinear control design. The DFL idea is to algebraically transform nonlinear system equations into linear ones, so that linear control techniques can be applied. The obtained controller is robust and the used model is independent from the operating point. Although, there may be a great variation in post-fault voltage and line reactance from the pre-fault, but they are assumed as a constant and specified value at this research [43, 51]. Therefore, this simplified assumption in the transient period is not a true one. Thus these values must be considered as uncertainties in the controller design. Wang et al. [42] improved the works which had carried out in [41] and assumed these values as parametric uncertainties. In other word, DFL is applied to the power system model to obtain a robust controller while it considers the uncertainties. The problem of designing controller finally transformed to the solving of an

Algebraic Riccati Equation (ARE) [53]-[55]. Solving an ARE results in the DFL compensating control law, as bellow:

$$v_{f1} = -K_{\delta}\Delta\delta - K_{\omega}\omega - K_{p}\Delta P_e \quad (3)$$

where $\Delta\delta$ is the estimated of un-measurable δ, and:

$$\begin{aligned} K_{.} &= f(x) \\ x &= [\Delta\delta\ \omega\,\Delta P_e] \end{aligned} \quad (4)$$

By differentiating terminal voltage equation in linearized dynamic model of power system, the equation (3) is obtained and represented in the term of x vector.

$K_{\delta}, K_P, K_{\omega}$ are linear gains which obtained from the ARE. By applying the linear control technique to dynamic model of power system in post-fault condition the voltage control law obtained as:

$$v_{f2} = -K_v\Delta v_t - K_{\omega}\omega - K_P\Delta P_e \quad (5)$$

where:

$$\begin{aligned} K_{.} &= f(y) \\ y &= [\Delta v_t\ \omega\,\Delta P_e] \end{aligned} \quad (6)$$

Satisfactory voltage regulation and transient stability were achieved by using switching strategy in [41], [42]. When a fault occurred in system the control signal v_{f1} with (3) is employed to keep the generators in synchronism. Then in the post-fault, the feedback law switched to (5) which is employed to enhance the power system performance [58], [59]. Fig. 5 shows the schematically implementation of this approach. When transient stability achieved a torque component which is in phase with rotor angle variation is removed from field voltage and thus its detrimental effect on LFOs damping eliminated. In other word, the switching strategy is used to enhance power system transient stability and small signal stability. In general, the control strategy of this category is not robust for wide range of disturbances. In addition, crude approach such as trial and error does not guarantee the best result. Thus, an attempt was conducted to solve the problems of this category.

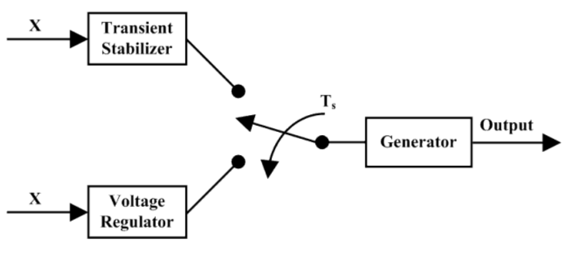


Fig. 5. Switching Strategy

The methods introduced in [43], [58] constitute the third category. Non-robustness drawback of second category methods solved by weighting the controller output based on operating point. Membership function or fuzzy approach employed to weight the controllers.

Guo et al. [58] introduced a global controller to improve transient stability and achieve satisfactory post-fault voltage level of power system when subjected to a wide range of sever disturbances. The following trapezoid-shaped like membership functions were used in the paper.

$$\begin{aligned} \mu_v(z) = &\left(1 - \frac{1}{1+exp(-120(z-o.o8))}\right). \\ &\cdot\left(\frac{1}{1+exp(-120(z+0.08))}\right) \end{aligned} \quad (7)$$

$$\mu_{\delta} = 1 - \mu_v \quad (8)$$

$$z = \sqrt{\alpha_1\omega^2 + \alpha_2(\Delta v_t)^2} \quad (9)$$

In the transient period, μ_{δ} becomes dominant value, and in the post-fault period μ_v gets its dominant value. According to the operating condition the control laws are weighted to get a satisfactory performance. Hence, the v_f input is defined as follows:

$$v_f = \mu_{\delta}v_{f1} + \mu_v v_{f2} \quad (10)$$

where:

v_{f1} is the control signal of DFL non linear-controller (3)

v_{f2} is the control signal of voltage regulator (5)

In other words, membership function determined the participation of each controller. This controller adapts itself with power system condition. The block diagram of global controller is shown in the Fig. 6.

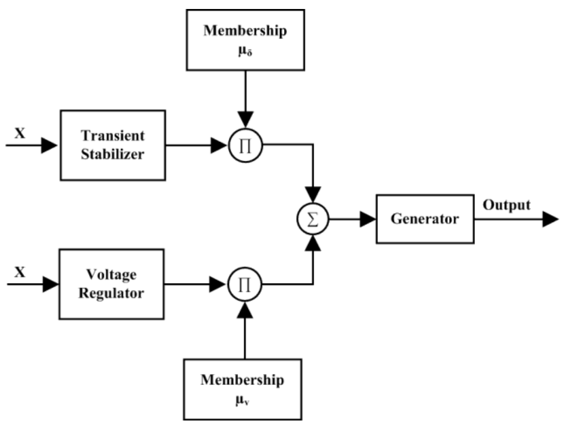


Fig. 6. Global controller model

The method introduced in [43] is also can be considered as an updated version of [58]. The robustness of voltage controller is achieved by using fuzzy approach and decision table. A fuzzy unit is implemented in algorithm to weight the controllers' action according to the fuzzification rules. The main problem associated with this category is in the case of controller complexity. In these methods an extra units is required to generate the weight or to take a decision.

In [60] (forth category) the problem of coordinating AVR and PSS are formulated as an optimization problem. The particle swarm optimization (PSO) technique is used to solve the problem. The PSO was discovered through simulation of a simplified social model. Several features of PSO, i.e. less computation time and few memory requirements, make it attractive for optimization problem. The paper considers multi-machines system to show efficiency of the proposed model. The model aims to minimize the comprehensive damping index (CDI):

$$CDI = \sum_{i=0}^{n} 1 - \xi_i \quad (11)$$

The proposed model used eigenvalues when the system linearized around an operating point. Regarding to the previous discussion, linearized model could be suitable when the system parameters specified completely. But, the introduced method does not consider these uncertainties by the proper model. Another problem which reduces the efficiency of the model is the simplified assumption on exciter model. The exciter is modeled only by a constant gain in the paper. This proposed algorithm computes the controller parameters for several pre-specified contingencies. To achieve a satisfactory performance in wide range of disturbances, the power system controller must be educated via heurist method (e.g. genetic algorithm) to select the best parameters at any condition. Therefore, the controller implementation becomes very difficult.

The final category which seems to be appropriate methods for designing robust controller in respect to the uncertainties consist of methods introduced in [6], [34], [40], [44]. Heniche et al. [40] used desensitized controller to design voltage controller. Desensitivity principles is based on linear quadratic Gaussian (LQG) where the quadratic index to be minimized is increased by the sensitivities. It is a method to design a robust controller while taking to account the parametric uncertainties. Here, first the LQR is described then the properties of desensitized controller are depicted.

Additive white Gaussian noise and quadratic costs are used to model uncertain linear systems and incomplete state information in LQG method. The method combined the Kalman filter with linear-quadratic regulator. Consider a general state equation of a linear model:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + \alpha(t) \\ y(t) &= Cx(t) + \beta(t) \end{aligned} \quad (12)$$

As control criteria, we take the scalar quadratic loss function:

$$J = \lim_{T\to\infty} \frac{1}{T} E\left[x^T(t) Q_c(t) + u^T(t) R_c u(t)\right] dt \quad (13)$$

The controller design is transformed to the problem of finding a control strategy for system (12) which minimizes (13) [42]. The controller which could minimize (13) is specified by the following equations:

$$\begin{aligned} \dot{x} &= Ax(t) + Bu(t) + k(t)y(t) - C(t)x(t) \\ u(t) &= -L(t)x(t) \end{aligned} \quad (14)$$

The matrix $K(t)$ is called the Kalman gain of the associated Kalman filter. The Kalman filter is a recursive filter which generate the state of a dynamic system at any moment by using past measurements. In other word, Kalman filter is a recursive estimator. Therefore, controller design is transformed to finding a regulator gain, K, which minimizes equation (13). Finding optimum value for K is not straightforward. Thus, the off-line iterative method is employed to obtain the gain. This controller named desensitized controller. The block diagram of desensitized controller has been depicted in the Fig. 7. This method is robust with respect to the small disturbances. The LQG controller is a dynamic system with same state dimension with the controlled system. Therefore, for a realistic power system with large state dimension, desensitized controller is not appropriate choice [40].

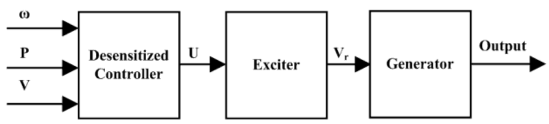


Fig. 7. Desensitized Controllers

The paper by Boules et al. [34] is actually another version of [40]. In this work the controller which introduced in [34] is applied to a multi-machine system. However, the problem which is associated with [40] yet exists in this paper.

Although most of these approaches have been proposed based on new contribution in modern control systems theory, they are not well suited to meet the design objectives in a real multi-machine power system because of the following two main reasons:

1- The complexity of control structure, numerous unknown design parameters and neglecting real constraints can be frequently seen in the most of new suggested techniques. While in real power systems, usually controllers with simple structure are desirable.
2- Experience shows that although the conventional PSS and AVR systems are incapable of obtaining good dynamical performances for a wide range of

operating conditions and disturbances, the electric power industry is too conservative to open the conventional control loops and test the novel/advanced controllers because of some probable risks, bugs and/or having a complex structure.

The above challenges is solved in [6], [44] by providing additional simple gain vector in parallel with conventional control devices. The design objectives are formulated via an H∞-SOF (H∞ static output feedback) control problem and the optimal static gains are obtained using an ILMI (iterative linear matrix inequalities) algorithm. Firstly, a brief review of H∞-SOF is introduced.

In [6], the power system dynamics is formulated as a linear time invariant system $G(s)$ with the following state-space realization:

$$\begin{aligned} \dot{x}_i &= A_i x_i + B_{1i} w_i + B_{2i} u_i \\ z_i &= C_{1i} x_i + D_{12i} u_i \\ y_i &= C_{2i} x_i \end{aligned} \qquad (15)$$

The H∞-SOF control problem for the linear time invariant system $G_i(s)$ with the state-space realization of (15) is to find a gain matrix $(y_i = K_i y_i)$, such that the resulted closed-loop system is internally stable, and the H∞ norm from wi to z_i (Fig. 8) is smaller than a specified positive number (γ), i.e.

$$T_{ziwi\infty} < \gamma \qquad (16)$$

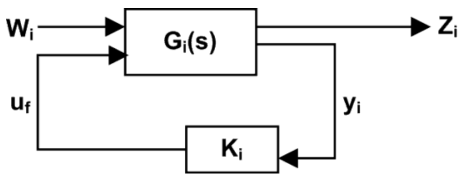


Fig. 8. Closed-loop system via H∞-SOF control

It is notable that the H∞-SOF control problem can be transferred to a generalized SOF stabilization problem which is expressed via the following theorem [63] (17).

$$\begin{bmatrix} A^T x + xA - PBB^T x - xBB^T P + PBB^T P & \left(B^T x + K_i C\right)^T \\ B^T x + K_i C & -I \end{bmatrix} < 0$$

Since a solution for the consequent non-convex optimization problem (17) cannot be directly achieved by using general and convex LMI techniques [66]-[68] a variety of methods were proposed by many researchers with many analytical and numerical methods to approach a local/ global solution. In [6], to solve the resulted SOF problem, an iterative LMI is used based on the existence necessary and sufficient condition for SOF stabilization, via the H∞ control technique.

The overall control structure using SOF control design for an assumed power system has been shown in the Fig. 9, where blocks PSS and AVR represents the existing conventional power system stabilizer and voltage regulators.

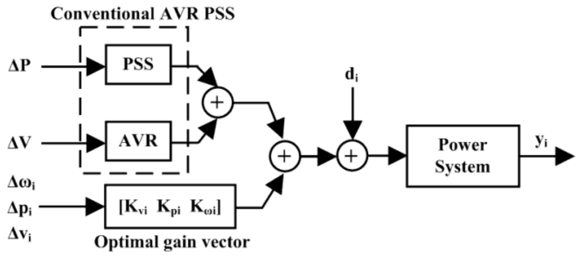


Fig. 9. Overall control structure

Using the linearized model for power system and performing the standard H∞-SOF configuration with considering appropriate controlled output signals, results an effective control framework, which has been shown in the Fig. 10.

The proposed coordination through a new optimal feedback loop has brought a significant improvement to power system performance and has increased the stable region of operation. The resulting controller is not only robust but it also allows direct effective trade-off between voltage regulation and damping performance.

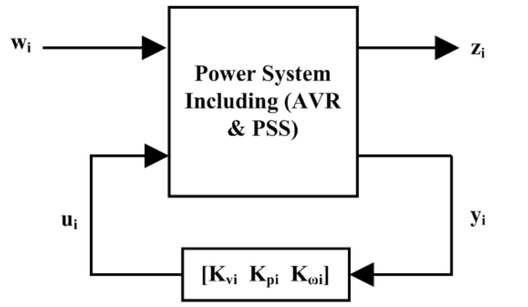


Fig. 10. The proposed H∞-SOF control framework

Furthermore, because of simplicity of structure, decentralized property, ease of formulation and flexibility, the design methodology can be practically implemented. Experimental results from implementation of the method on the analog power system simulator demonstrate the efficiency of the method.

III. Research Needs

A complete knowledge about power system dynamics, i.e. generator model, exciter and PSS model, and robust control strategies are required to design an appropriate controller. Some important aspect, i.e. simplicity of designed controller, considering parametric uncertainties and practical constraints, must be taking into account in the designing process. Neglecting of each one in the case of simplicity, make the controller to be far from practice.

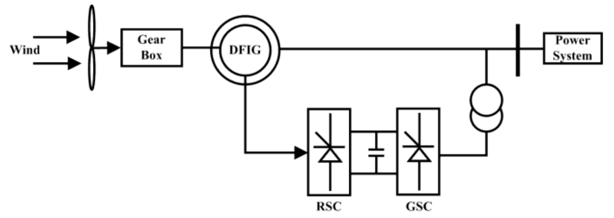


Fig. 11. DFIG System

IV. RESs and Their Effects

The increasing need for electrical energy in the twenty-first century, as well as limited fossil fuel reserves and the increasing concerns with environmental issues for the reduction of carbon dioxide (CO_2) and other greenhouse gasses, call for fast development in the area of RESs. Renewable energy is derived from natural sources such as the sun, wind, hydro-power, biomass, geothermal, oceans, and fuel cells that replenished themselves over a relatively short period of time. As the use of renewable energy resources (RESs) increases worldwide, there is rising interest in study of their impacts on power system operation and control [65].

Wind power is recognized as the most important RES because of its economical and technical prospects [66]. Conventionally, squirrel cage induction generators with fixed speed (FSIG) are used in the wind farms. However, low efficiency of this type after fault, limited its usage. Hence, variables wind turbine equipped with frequency convertor is used instead of older one. Some features of doubly fed asynchronous generator (DFIG), i.e. higher energy transfer capability, low investment and flexible control, make it the most popular scheme for variable speed wind turbine [67], [68]. The rotor wound is feed via a series of voltage source convertor in the DFIG structure. The converters consist of a rotor-side converter (RSC) and a grid-side converter (GSC). The controllability of these converters provides an extra control device. A typical DFIG system has been illustrated in the Fig. 11.

Back to back convertor which employed to connect rotor to the grid, provides controllability on the rotor voltage, rotor phase angle, and then controllability on terminal voltage and electrical power. Therefore, two independent control signals are available to satisfy voltage regulation and improve small signal stability. In other word, AVR manipulates rotor voltage magnitude and PSS manipulates rotor angle. Thus, a tradeoff between AVR and PSS is not required in DFIGs. Furthermore, network oscillations cause variations in the injected current into the network by DFIGs. This induces an extra current component in the damper of synchronous generator. Thus, damper current and oscillations damping rate is increased. Increasing damper current is a fundamental task of PSS in the DFIG. In other word, PSSs are employed in DFIGs to engender increased damping torques in the synchronous generators.

Replacing synchronous generators which are equipped with PSS by DFIGs affect dynamics of power system. This introduces some new modes in power system and thereby power system encounters with new challenge.

Behavior of power system following a disturbance is determined by the interaction between synchronizing forces and the power system inertia. In the power system only synchronous generators participate in the specification of system inertia. DFIGs are connected to a grid by power electronics devices. Therefore, in DFIGs, the inertia of the turbine effectively decoupled from the system. Replacing synchronous generators with DFIGs decrease the total power system inertia. Therefore, with the increased penetration of DFIG, the reliability of power system after large disturbances effectively is affected [66].

A substantial study in the case of small signal stability and transient stability with increasing penetration of DFIGs has been done in [66]. It used the sensitivity of Eigen-value with respect to inertia to demonstrate DFIGs impact on small signal stability. Experimental results show that increasing penetration had detrimental impact on a specified mode while had beneficial impact for another modes. However, the detrimental impact of increasing penetration is in concern. First in the conventional power system the mode which had detrimental impact on damping is specified by means of sensitivity. Then it was described that increasing penetration of DFIGs may reduce the stability margin of overall system. In other word damping ration for the mentioned mode is decreased. For the transient stability analysis, participation factor of each generators are determined in the specified mode. Then the generator with greater participation factor is selected and a large disturbance is applied to its related bus. This cause the mode with detrimental effect be excited. It was shown that increasing penetration of DFIGs decrease the damping ratio in case of large disturbances. Although, damping ratio is decreased by increasing wind power, but frequency oscillation in the power system is constant. The oscillation frequency in the analysis belongs to the inter-area range, and increasing penetration affect the behavior of inter-area oscillations [66].

Tsourakis et al. [67] used a test case to prove the beneficial impact of increasing penetration of wind farm on damping ratio. The paper shows that increasing of DFIG based wind farms increases oscillation damping, but not for all of penetration. In this case, voltage control of DFIG via adjustment of rotor voltage magnitude decreases the damping ratio [69].

Impact of DFIG on power system oscillation is presented in [73]-[82]. In all of these works, the authors were claimed that the DFIG-based wind turbines have small negative effect on damping of inter area mode of interconnected power system. Some of these studies [75]-[78] used an auxiliary control loop such as PSS to enhance electromechanical oscillation damping. However, no attempt is conducted to coordinate AVR-PSS by increasing penetration of DFIGs.

V. Conclusion

Sufficient damping and synchronizing torques in a power system ensure stable operation of the system after a sever fault. AVRs provide the required synchronizing torque to regain transient stability after a disturbance. Although AVR increases synchronizing torque, it injects a negative damping torque component to the system, cause to the multiple swing instability. PSSs are employed in power system to compensate the detrimental effects of AVRs.

AVR and PSS employ the field voltage to produce torques which are not in phase. Thus, only a control signal is available to improve two conflict behavior of the system. Therefore, a tradeoff between these requirements is needed. The AVR and PSS parameters are tuned to have satisfactory performance in the operating point. By change in the operating point, AVR or PSS performance are deteriorated and stability of power system after a fault will be in concern. Therefore, combination of AVR and PSS must be sufficiently robust against variation of operating point to ensure the stability for a wide range of probable faults.

Concurrent with increased attention to the environmental concerns and attempts to reduce dependency on fusil fuel, RESs are known as the new power sources. Among the various renewable sources, wind power is assumed to have the most favorable technical and economical prospects. In small scale studies, the impact of wind turbine generator is negligible. However, with the increasing penetration of DFIG-based wind farms into the grid, the dynamic performance of the power system can be affected. Furthermore, uncertainties which imposed to power system are increased by increasing penetration of DFIG-based wind farms into the grid. Therefore, RESs and particularly wind farm effects must be considered in the performance and designing of AVR, PSS and co-ordination of them.

This paper focused on review of the recent researches in the field of AVR and PSS coordination. Although AVR and PSS coordination is an important issue in stability and dynamic prospects, lack of a realistic analyzing in a power system with RESs can be clearly seen.

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Authors' information

Department of Electrical and Computer Engineering, University of Kurdistan, Sanandaj, Iran.

Hêmin Golpîra is currently working toward the M.S. degree in electrical engineering at the University of Kurdistan, Sanandaj, Iran. His current research interests include the coordination of AVR and PSS in the presence of Renewable Energy Sources (RESs).

Hassan Bevrani received the M.Eng. (Hons.) and the Ph.D. degrees in Electrical Engineering from K. N. Toosi University of Technology (Iran , 1997) and Osaka University (Japan , 2004), respectively. Since 2004, he has held postdoctoral fellow and senior research fellow positions in Kumamoto University (Japan: 2004-2006) and Queensland University of Technology (Australia: 2007-2008). Currently, he is a visiting professor at Kumamoto University (Japan). His special fields of interest include robust load-frequency control and robust/intelligent control applications in Power system and Power electronic industry.

Ali Hessami Naghshbandy received the B.S., M.S., Ph.D. degrees all in Electrical Engineering from Iran University of Science and technology, Iran in 1994, 2000 and 2008 respectively. He is presently an Assistant Professor of Electrical Engineering at University of Kurdistan, Sanandaj, Iran. His research interests include power system dynamics and stability, nonlinear systems theory, optimization and power system planning and operations. He is a member of IEEE and CIGRE.

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