Global Control of Stressed Power Systems

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Abstract– A multilevel control scheme that is capable of system control over wide ranges of operating conditions for nonlinear systems is proposed. The first control level confines the system operation to some reference segments in its state space. Each reference segment is further subdivided using bifurcation analysis for establishing the bounds on regions of the state space of the system with different control requirements. The principles of global control lead to a hierarchical control structure which combines regional (linear or nonlinear) controllers smoothly. The scheme is illustrated for control of a power system known to have complex dynamical behavior for a wide range of loading levels.

1 Introduction

In general, a nonlinear system may behave qualitatively differently in different operating regions. These qualitative differences call for a different control action in each region. For such a system, a control scheme capable of control over a wide range of operating conditions must be employed. Such a scheme can be referred to as a *global control* strategy. To achieve proper global control, a global view of the nonlinear system needs to be taken into consideration. Such a view should be based on the limits at which qualitative changes in nonlinear system behavior occur and the dynamics of the system in different operating regions. The limits at which qualitative changes in nonlinear system behavior occur can be related to structural stability of the system and alternatively to bifurcation points in its mathematical model.

Power systems present a rich source of problems in the control of nonlinear systems. In power systems, the effects of bifurcations on voltage instabilities and collapse are well established; for example, see [7] and references therein. Voltage collapse may be associated with saddle-node bifurcation where equilibria are lost [8]. Other forms of bifurcations in power systems have also been considered, among which the Hopf bifurcation is probably the most important one. The implications in design of feedback control for static bifurcations have been reported in [3, 9]. The design of feedback laws which render a subcritical Hopf bifurcation supercritical, locally for small variations of the bifurcation parameter has been considered in [2].

In this work, we consider a multilevel control scheme. The higher level based on switching control strategies, introduces some new state space segments for the system trajectories to converge to. This will allow for operation beyond the nominal saddle-node bifurcation point of the plant. The lower level, consisting of several regional controllers, secures desirable system performance in the presence of a subcritical Hopf bifurcation. To design some regional controllers the Hopf bifurcation and center manifold theorems are utilized for derivation of stability results.

This paper is organized as follows; a brief overview of nonlinear system bifurcations and the bifurcating power system model are presented in Section 2. Section 3 introduces various control objectives. Section 4 proposes several global control laws to meet various objectives and demonstrates how they result in voltage regulation and stability enhancement of the power system. The final section gives the concluding remarks.

2 Bifurcation model

2.1 Bifurcation analysis

Bifurcation analysis provides a means for studying dynamic mechanisms which may change structural stability of the system as some parameter varies slowly with time. At a bifurcation point the structural stability of the system is lost. That is, the parameter space of a nonlinear system can be considered as the composition of structurally stable regions which are bounded by bifurcation points or surfaces. Consider a nonlinear system presented by a number of coupled differential-algebraic equations as

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{f}(\mathbf{x}(t),\, \mathbf{a}(t),\, \nu(t),\, u(\mathbf{x},\, \mathbf{a}, t)), \\ 0 &= \xi(\mathbf{x}(t),\, \mathbf{a}(t),\, \nu(t),\, u(\mathbf{x},\, \mathbf{a}, t)), \\ y &= h(\mathbf{x}(t),\, \mathbf{a}(t),\, \nu(t),\, u(\mathbf{x},\, \mathbf{a}, t)); \end{aligned} \qquad (1)$$

where $\mathbf{x} \in \mathcal{R}^n$ are the dynamic state variables initially at $\mathbf{x}_0$, $\mathbf{a} \in \mathcal{R}^m$ are the algebraically constrained variables, $y \in \mathcal{R}$ denotes the system output, and $\nu \in \mathcal{R}$ is some varying system parameter. The variations of the control input u is considered to be of feedback type.

In the vicinity of an equilibrium point, the trajectories of (1) can be locally defined by the reduced order

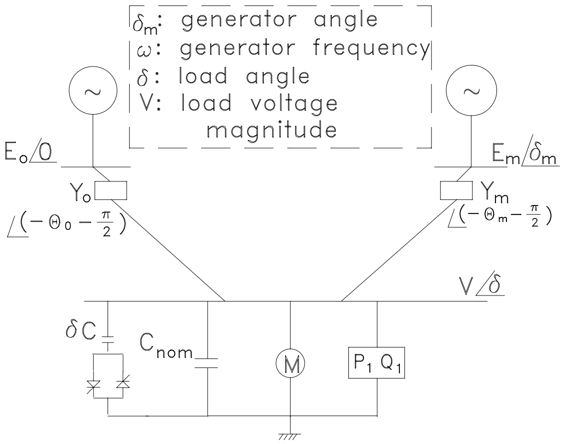

Figure 1: Power system example

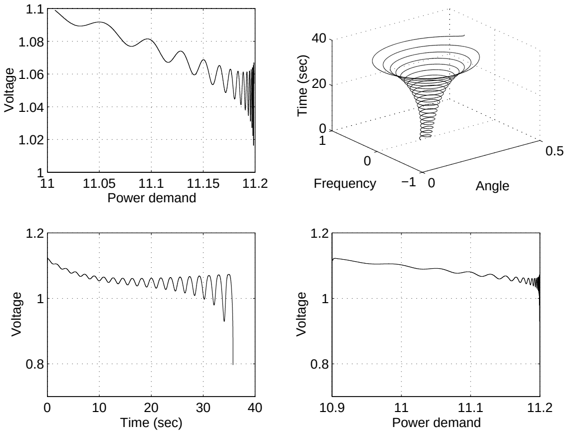

Figure 2: Oscillatory instability

differential system

$$\dot{\mathbf{x}} = \hat{\mathbf{f}}(\mathbf{x}, u; \nu); \tag{2}$$

where

$$D_{\mathbf{x}}\hat{\mathbf{f}} = D_{\mathbf{x}}\mathbf{f} - D_{\mathbf{a}}\mathbf{f}\,(D_{\mathbf{a}}\xi)^{-1}\,D_{\mathbf{x}}\xi; \tag{3}$$

provided $D_{\mathbf{a}}\xi$ is not singular.

For these models, a saddle-node bifurcation occurs when a non-hyperbolic equilibrium point has a simple zero eigenvalue at the bifurcation point $\nu = \nu_{SN}$; additionally transversality conditions must be satisfied [6]. When the motion is periodic (e.g. limit cycles), the bifurcation separating it from a stable equilibria is the Hopf bifurcation. The branch of periodic orbits emerging from the equilibrium point may consist of stable oscillations as a result of a supercritical bifurcation or they may be unstable arising from a subcritical bifurcation [6].

2.2 Power system example

A power system example from [4] is shown in Fig. 1; where for later reference, we have also included a thyristor controlled shunt capacitor. This example has simple structure but has been shown to exhibit a rich diversity of dynamic behavior as its reactive load power Q_1 considered as the bifurcation parameter changes; for example, see [7]. With $\delta C = 0$ and other parameter values as chosen in [4], it has been shown that the power system undergoes a subcritical Hopf bifurcation at $Q_{1UH} = 10.98$. The system exhibits a supercritical Hopf bifurcation at $Q_{1SH} = 11.41$, which is followed closely by the saddle-node bifurcation Q_{1SN}.

For the power system example in equilibrium with Q_1 near Q_{1SN}, if any perturbations take the operating point beyond the saddle-node, a fast monotonous divergence (i.e. a voltage collapse) can be expected. If the equilibrium point can be characterized by $Q_{1UH} \leq Q_1 < Q_{1SH}$, the operating point will diverge from the (unstable) equilibrium point through growing oscillations as shown in Fig. 2. For the operating point being very close to the equilibrium point corresponding to the supercritical Hopf bifurcation, an orbitally stable response can be expected. The equilibrium points corresponding to power loadings $Q_{1SH} \leq Q_1 < Q_{1SN}$ are stable operating points, although highly sensitive.

3 Bifurcation control problem

3.1 Control objectives

For power systems, control in the presence of bifurcations is usually achieved by ensuring that the system operation is such that the bifurcation parameter is always below its critical values. In such a case, the bifurcations are ultimately avoided; for example, see [5]. More generally, the local control of a system exhibiting Hopf bifurcation may involve the design of feedback laws to delay (to higher values of the bifurcation parameter) or to eliminate the bifurcation. It may also imply rendering a subcritical Hopf bifurcation to be supercritical with restrained amplitude of the (stabilized) bifurcated solutions. While such controllers allow for system operation near a bifurcation point, they are still fundamentally of a local nature. Additionally, to achieve operation beyond the nominal saddle-node bifurcation point, it is required to introduce some fixed point or oscillatory states for the system trajectories to converge to. So, the bifurcation control problem can be considered as the design of control laws that constrain the system state to some certain operating region $\mathbf{X}_d$, containing stable (and stabilized) fixed point or oscillatory operating states as ν varies quasi-statically with time within a certain range of interest Ω_d

$$\Omega_d = \{\nu \mid \nu^{min} \leq \nu \leq \nu^{max}\}. \tag{4}$$

Correspondingly, it is possible to define a region of interest (or viability region) for the output y_d, as

$$Y_d = \{y_d \mid y_d^{min} \leq y_d \leq y_d^{max}\}. \tag{5}$$

These regions may contain equilibrium points and oscillatory solutions with different stability characteristics. That is, as ν varies within its limits, the open loop system may undergo bifurcations.

3.2 State space segmentation

Consider some reference state space segment $\mathbf{X}_r \subset \mathbf{X}_d$ consisting of equilibrium points $\mathbf{x}_{e,r}$ (stable or to be stabilized) that must be tracked by the states as the parameters vary. Such a segment of system (2) as ν varies can be described by

$$\hat{\mathbf{f}}(\mathbf{x}_{e,r}(t), u_{e,r}; \nu(t)) = \mathbf{0}, \tag{6}$$

where $u_{e,r}$ is the properly specified reference control at the equilibria and

$$u = u_{e,r} + \delta u_r. \tag{7}$$

In general, it may be necessary to establish k ($k \geq 1$) such segments by appropriately choosing $u_{e,r} = u_{e,j}$ ($j = 1, 2, \cdots, k$) so that for all $\nu \in \Omega_d$, at least one $\mathbf{x}_e \in \mathbf{X}_d$ can be achieved.

The reference control $u_{e,r}$ may be a switching type control with relatively large impact on the equilibrium profile of the system. In the case of bifurcating systems, k switching controls which establish the required reference segments (i.e. so that $\forall \nu \in \Omega_d$, $\exists y_e \in Y_d$) must be identified. Each reference segment can then be characterized by the reference control $u_{e,j}$ that keeps the output within the viability range Y_d for a particular range of bifurcation parameter $\Omega_j = \{\nu \mid \nu_j^{min} \leq \nu \leq \nu_j^{max}\}$.

Consider the case where as ν increases, on a particular reference segment j with $u_{e,r} = u_{e,j}$ the system exhibits a subcritical Hopf bifurcation at $\nu = \nu_{UH,j}$, a supercritical Hopf bifurcation at $\nu = \nu_{SH,j}$, and a saddle-node bifurcation at $\nu = \nu_{SN,j}$. In that case, Ω_j may be considered as the union of the sets

$$\begin{aligned} \Omega_{UH,j} &= \{\nu \mid \nu_j^{min} \leq \nu < \nu_{UH,j}\}, \\ \Omega_{SH,j} &= \{\nu \mid \nu_{UH,j} \leq \nu < \nu_{SH,j}\}, \\ \Omega_{SN,j} &= \{\nu \mid \nu_{SH,j} \leq \nu < \nu_{SN,j}\}, \\ \Omega_j^{max} &= \{\nu \mid \nu_{SN,j} \leq \nu \leq \nu_j^{max}\}. \end{aligned} \tag{8}$$

If some of the bifurcations do not occur on a particular segment, the decomposition of Ω_j will be defined accordingly. It must be noted that, as there are no equilibrium points after a saddle-node on a particular segment, for feedback type control purposes the upper bound on Ω_j cannot be more than $\nu_{SN,j}$.

For a particular reference segment j with $u_{e,r} = u_{e,j}$, the structural stability properties of the nonlinear system provide insight as to how the state space further segmentation can be enhanced. In this case, for $\nu \in \Omega_{SH,j}$ feedback control $\hat{v}_j^i(\delta\mathbf{x}, \delta\nu^i)$ is used for stabilization; while before the subcritical Hopf bifurcation point ($\nu \in \Omega_{UH,j}$) the equilibria are stable attractors. For the supercritical Hopf bifurcation, transition of ν from region $\Omega_{SH,j}$ to region $\Omega_{SN,j}$, the situation is the opposite (although there are coexisting stable attractors in the vicinity of the equilibrium points). The structure of the feedback control to achieve tracking of nominally stable equilibria denoted as $v_j^i(\delta\mathbf{x}, \delta\nu^i)$ is not necessarily the same as $\hat{v}_j^i$. Obviously, to cover both cases of $\nu \in \Omega_{UH,j}$ and $\nu \in \Omega_{SN,j}$, the control v_j^i may have the same structure but with different parameters. Consequently, the unstable equilibrium points very close to Hopf bifurcation points are excellent candidates for further segmentation of the parameter space of the system into regions with different control requirements. The variations of the global control law (on a particular reference segment j) can be considered as $\delta u_j = \sum_{i=1}^n w_j^i \delta u_j^i$, with w_j^i representing properly identified weighting functions.

To identify the weighting functions, one approach which may turn out to be convenient to use in practice can be based on so-called fuzzy control. This will lead to a control scheme with some hierarchical structure. Based on the above discussion, for system operation on reference segment j, simple generic control rules can be established as

$R_{c,j}^i$: IF ν is F_ν^i
    THEN IF ν *is* $\Omega_{UH,j}$
        THEN $\delta u_j^i = v_j^i$
    ELSE IF ν *is* $\Omega_{SH,j}$
        THEN $\delta u_j^i = \hat{v}_j^i$
    ELSE IF ν *is* Ω_j^{max}
        THEN $\delta u_j^i = v_j^i$
    ELSE resort to other actions
        (e.g. hard switching or load shedding)

$$i = 1, 2, \cdots, n \tag{9}$$

where F_ν^i is a fuzzy set characterized by membership function μ_j^i, that is

$$F_\nu^i = \{\nu,\ \mu_j^i(\nu) \mid \nu \in \Omega_j\}. \tag{10}$$

Based on such local controllers the required variations of the global control law (on a particular reference segment j) can be considered as

$$\delta u_j = \frac{\sum_{i=1}^n \delta u_j^i \mu_j^i}{\sum_{i=1}^n \mu_j^i}; \tag{11}$$

which is of the form $\delta u_j = \sum_{i=1}^n w_j^i \delta u_j^i$.

3.3 Stabilization of oscillatory solutions

Consider the system (1) undergoing a Hopf bifurcation at $\nu = \nu_{UH}$, with critical eigenvalues of the system Jacobian (3) crossing the imaginary axis at $\pm j\beta$ while all other eigenvalues have strictly negative real parts. After the evaluation of the Jacobian $\mathbf{A}^{UH}$ at the subcritical Hopf point, the transformation matrix $\mathbf{B}^{UH}$ can be identified such that

$$\mathbf{J} = (\mathbf{B}^{UH})^{-1}\,\mathbf{A}^{UH}\,\mathbf{B}^{UH} = \left[\begin{array}{c|c} \mathbf{J}_c & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{J}_s \end{array}\right] = \left[\begin{array}{cc|ccc} 0 & -\beta & 0 & \cdots & 0 \\ \beta & 0 & 0 & \cdots & 0 \\ \hline 0 & 0 & -|\lambda_3| & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & \cdots & -|\lambda_n| \end{array}\right]. \qquad (12)$$

Introducing $\mathbf{r} = [r_1\, r_2\, \cdots, r_n]^T$, σ and w as

$$\mathbf{x} = \mathbf{B}^{UH}\cdot\mathbf{r} + \mathbf{x}_e^{UH},\; \nu = \sigma + \nu_{UH},\; u = w + u_e^{UH}; \quad (13)$$

the system can be recast in the form

$$\begin{aligned} \dot{\mathbf{r}}_c &= \mathbf{J}_c\mathbf{r}_c + \hat{\mathbf{f}}_c(\mathbf{r}_c, \mathbf{r}_s, \sigma, w), \\ \dot{\mathbf{r}}_s &= \mathbf{J}_s\mathbf{r}_s + \hat{\mathbf{f}}_s(\mathbf{r}_c, \mathbf{r}_s, \sigma, w); \end{aligned} \qquad (14)$$

where $\mathbf{r}_c = [r_1\; r_2]^T$ are the critical variables and $\mathbf{r}_s = [r_3,\; \cdots,\; r_n]^T$. The functions $\hat{\mathbf{f}}_c, \hat{\mathbf{f}}_s$ and their derivatives vanish at the origin. These transformations result in a coordinate translation to shift the equilibria to the origin while splitting the linear part of the equations. By the center manifold theorem [6] it can be ascertained that in the vicinity of the origin a smooth invariant manifold $\mathbf{r_s} = \mathbf{h}(\mathbf{r}_c, \sigma, w)$ for (14) exists. This center manifold is tangent to the eigenspace of the linearized system $\mathbf{J}_c$, with $\mathbf{h}(\mathbf{0}, \sigma, w) = \mathbf{h}'(\mathbf{0}, \sigma, w) = \mathbf{0}$. Substituting the manifold constraint into the first part of (14), the bifurcation equations can be obtained as

$$\dot{\mathbf{r}}_c = \mathbf{J}_c\mathbf{r}_c + \hat{\mathbf{f}}_c(\mathbf{r}_c, \mathbf{h}(\mathbf{r}_c, \sigma, w), \sigma, w). \qquad (15)$$

With $\mathbf{J}_s$ a stable matrix, the local stability behavior of the system is governed by the reduced model (15). For notational simplicity, let $\mathbf{r}_c = [x\; z]^T$ and denote the functions in (15) by $f(\cdot)$ and $g(\cdot)$. So, the bifurcation equations can now be considered as

$$\begin{aligned} \dot{x} &= f(x, z, \sigma, w), \\ \dot{z} &= g(x, z, \sigma, w). \end{aligned} \qquad (16)$$

Carrying out the Taylor expansion of (16) it can be shown that the real part of the critical eigenvalues will be

$$\alpha(\sigma, w) = \frac{1}{2}[f_w w_x + g_w w_z + \sigma(f_{\sigma x} + g_{\sigma z})]; \qquad (17)$$

and its rate of change with respect to bifurcation parameter (in the absence of any control effort) is

$$\alpha_1 \equiv \frac{d}{d\sigma}[Re(\lambda(\sigma)]|_{\sigma=0} = (f_{\sigma x} + g_{\sigma z}) \qquad (18)$$

Now, let the stability coefficient S be defined as

$$S = \frac{1}{16}[f_{xxx} + g_{xxz} + f_{xzz} + g_{zzz}] + \frac{[f_{xz}(f_{xx} + f_{zz}) - g_{xz}(g_{xx} + g_{zz}) - f_{xx}g_{xx} + f_{zz}g_{zz}]}{16\beta}. \qquad (19)$$

The Hopf bifurcation theorem [6] establishes that with $\alpha_1 \neq 0$, if the genericity condition $S|_{x=z=\sigma=0} \neq 0$ is also satisfied, a curve of periodic solutions bifurcates from the origin into $\sigma < 0$ provided $S\alpha_1$ is positive or into $\sigma > 0$ if $S\alpha_1$ is negative. If α_1 is negative, the origin is stable for $\sigma > 0$ and unstable for $\sigma < 0$; while for α_1 positive, the origin is stable for $\sigma < 0$ and unstable for $\sigma > 0$. The periodic solutions on the side of $\sigma = 0$ for which they exist, are stable if the origin is unstable and vice versa. The amplitude of the periodic orbits near the bifurcation point is $\left|\frac{\alpha_1\sigma}{S}\right|^{\frac{1}{2}}$ with period $\frac{2\pi}{|\beta|}$.

For nonzero control effort, the stability coefficient S_w (to be evaluated at the origin) will be

$$S_w = S + \frac{[(w_{xxx} + w_{xzz})f_w + (w_{zzz} + w_{xxz})g_w]}{16} + \frac{[w_{xz}(f_w^2 - g_w^2)(w_{xx} + w_{zz}) + f_w g_w(w_{zz}^2 - w_{xx}^2)]}{16\beta}. \qquad (20)$$

From this relation and (17) it is evident that only the feedback of critical variables up to cubic terms may have any effect on the existence of a Hopf bifurcation or changing the stability behavior of the bifurcated solutions. Obviously, even for a system with controllable modes only linear terms have any effect on the location of the eigenvalues. Consequently, to change a subcritical bifurcation to a supercritical one, using (20), quadratic and/or cubic (critical) state feedback can be identified. It is also straightforward to show that for a system with uncontrollable modes, only the feedback of the square of the critical variables has any effect on the stability behavior of the bifurcated solutions.

4 Control of power system example

The power system described previously is now considered to be equipped with a combination of fixed and thyristor-controlled capacitors as shown in Fig. 1. The fixed capacitors may be switched by circuit breakers to some particular nominal value. Small changes from such nominal values are obtained by controlling the firing and conduction time of oppositely poled thyristors. In this way, the controlled variable can be regarded as the shunt capacitance; the nominal values correspond to different values for $u_{e,r}$ and the small changes of capacitance are considered as δu_r.

The bifurcation diagrams of this system for several (integer) values of capacitance are shown in Fig. 3; for

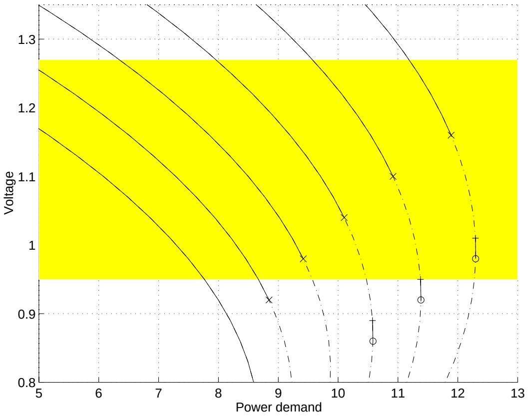

Figure 3: Bifurcation diagrams, $C_{nom} = 8, 9, 10, 11, 12, 13$ (x: subcritical Hopf, +: supercritical Hopf, o: saddle-node bifurcation)

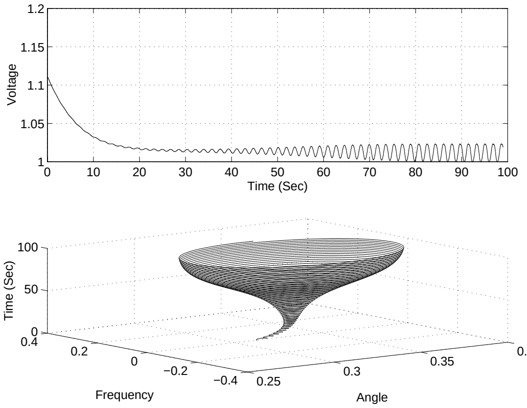

Figure 4: Cubic control of power system model to render the subcritical Hopf bifurcation to be supercritical

readability, the oscillatory responses have been omitted. In this figure, the dashed lines represent the unstable equilibria. The load voltage V, is taken as the output, and its acceptable viability region is also shown in this figure. Clearly, to lower the value of the maximum allowable load voltage other reference segments, between the established ones, can be included.

4.1 Reduction to normal form

To utilize nonlinear control laws, the power system model needs to be put in normal form. With $\delta\mathbf{x}$ as the deviation of the state $\mathbf{x} = [\delta_m \ \omega \ \delta \ V]^T$ from the load dependent equilibria, the linearization of the power system model can be carried out. Using the eigenvectors of the system Jacobian $\mathbf{A}^{UH}$ evaluated at the subcritical Hopf point (with $C_{nom} = 12$) the transformation matrix $\mathbf{B}^{UH}$ can be defined such that

$$\mathbf{J} = (\mathbf{B}^{UH})^{-1} \, \mathbf{A}^{UH} \, \mathbf{B}^{UH}. \tag{21}$$

To examine the local dynamical behavior of the power system near the subcritical Hopf bifurcation point, the transformations and the results from center manifold theorem outlined in section 3.3 can be used to establish equations in the form of (15) or (16) (with $[x \ \ z] = [r_1 \ r_2]$).

4.2 Nonlinear control

Use of nonlinear control to render the subcritical Hopf bifurcation to be supercritical will need to alter the sign of the stability coefficient S in (19). It is worth reiterating that the feedback control will not change the (positive) value of α_1 in (18). So, for the control established by quadratic feedback of critical variables

$$w = k_1 \, r_1^2 + k_2 \, r_2^2; \tag{22}$$

the stability coefficient can be seen to be $S_w = 0.002396 + 0.073\,(k_1^2 - k_2^2)$. With $k_1 = 1$ and $k_2 = 3$, this will correspond to a negative value resulting in stabilized oscillatory responses. It can be shown that the modes of the system are related to controllable eigenvalues. Therefore, the same type of results can be achieved by cubic feedback of critical variables

$$w = k_1 \, r_1^3 + k_2 \, r_2^3. \tag{23}$$

The hierarchical control law (9) can now be modified so that the control in region Ω_{SH} is established by these nonlinear control laws. For example, the stabilized oscillations in Fig. 4 are the consequences of the control law (23) with $k_1 = -1$ and $k_2 = 1$. The other conditions are the same as those resulting in the response displayed in Fig. 2.

By considering a linear controller for region Ω_{UH} and nonlinear control laws for region Ω_{SH} the subcritical Hopf bifurcation can be delayed (as the critical modes are controllable) and also rendered supercritical. For instance, shifting the critical poles to the left of the imaginary axis by $\epsilon = 0.2$ (by linear control) and implementing the quadratic feedback (22) results in stabilized (oscillatory) bifurcated solutions as shown in Fig. 5. It is easy to show that the emerging Hopf bifurcation is rendered supercritical and is also delayed to $Q_1 = 11.02$.

From Fig. 3 it is evident that for the first two reference segments (with $C_{nom} = 8$ or 9) the equilibria within the voltage viability region are stable and no bifurcation takes place. Consequently, the first level of control consisting of switching between different nominal capacitance values (based on power demand and voltage levels) will be able to achieve voltage stability. For other segments corresponding to higher values of power demand, the hierarchical control scheme must be additionally utilized as the segments contain bifurcations. For these cases and for each nominal value of capaci-

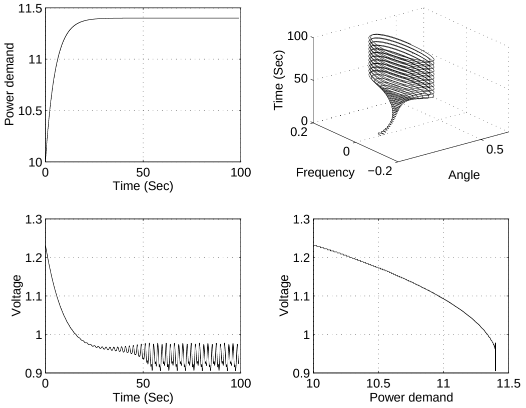

Figure 5: Hierarchical control of power system model to delay the subcritical Hopf bifurcation and render it supercritical

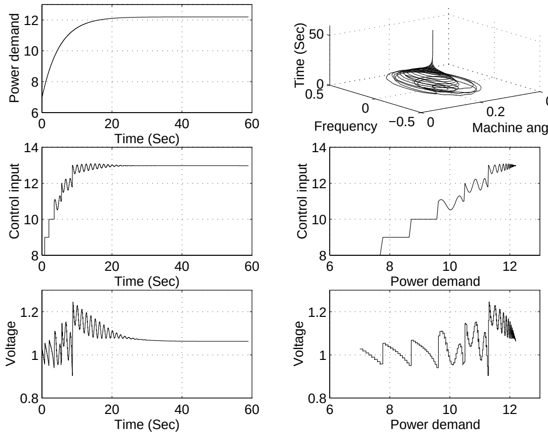

Figure 6: Controlled system response (multilevel control)

tance, weighting functions and control laws are identified in the same manner as that described for the above case. The results of such combinatory and multilevel control are shown in Fig. 6. The enhanced capability of voltage regulation over the wide range of power demand changes can be noticed.

5 Conclusion

In this paper, we have developed a framework for design of control laws for a parameter dependent nonlinear system. The control scheme, referred to as global control, facilitates the system operation for a wide range of parameter variations. In particular, we have derived various linear and nonlinear control laws for elimination, delay or stabilization of the bifurcated solutions of the subcritical Hopf bifurcation. Additionally, the proposed controller is capable of switching between several reference trajectories allowing for system operation beyond the saddle-node bifurcation point of the open loop system. The result is a global multilevel control scheme, where the first level depending on signal levels switches the control, so that the system states are confined to the neighborhood of some desired reference segment. For each reference segment, the information gained through bifurcation analysis is used for further segmentation of the state space of the system. Based on that, the appropriate regional control laws are identified and properly blended to establish the global control law. It has also been demonstrated that the utilization of the proposed global control scheme significantly improves the power system stability and voltage regulation capabilities for a wide range of loading levels. The general principles of global control clearly show the considerable potential of providing an integrated framework for security control and steady-state control of power systems.

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