# Design and Analysis of an Adaptive Power System Stabilizer

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**Abstract**

Power system stabilizers (PSS) must be capable of providing appropriate stabilization signals over a broad range of operating conditions and disturbances. Traditional PSS rely on robust linear design methods. In an attempt to cover a wider range of operating conditions, expert or rule-based controllers have also been proposed. Recently, fuzzy logic as a novel robust control design method has shown promising results. The emphasis in fuzzy control design centers around uncertainties in system parameters and operating conditions. Such an emphasis is of particular relevance as the difficulty of accurately modelling the connected generation is expected to increase under power industry deregulation.

## Introduction

Fuzzy logic controllers are based on empirical control rules. In this paper, a systematic approach to fuzzy logic control design is proposed Implementation for a specific machine requires specification of performance criteria. This performance criteria translates into three controller parameters which can be calculated off-line or computed in real-time in response to system changes. The robustness of the controller is emphasized. Small signal and transient analysis methods are discussed. This work is directed at developing robust stabilizer design and analysis methods appropriate when fuzzy logic is applied.

Power system stabilizers (PSS) must be capable of providing appropriate stabilization signals over a broad range of operating conditions and disturbances. A traditional power system stabilizer (PSS) provides a positive damping torque [1,2] in phase with the speed signal to cancel the ePect of the system negative damping torque. Because the gains of this controller are determined for a particular operating condition, they may not be valid for a wide range of operating conditions. Considerable efforts have been directed towards developing adaptive PSS, e.g. [3,4) In an attempt to cover a wide range of operating conditions, expeG or rule-based controllers have been proposed for PSS [5] Recently, the introduction of fuzzy logic into these rule-based controllers has shown promising results [6,7].

Control algorithms based on fuzzy logic have been implemented in many processes [8,9]. The application of such control techniques has been motivated by the desire for one or more of the following: (1) improved robustness over that obtained using conventional linear control algorithms, (2) simplified control design for diGcult to model systems, e.g., the truck backer-upper problem [10], and (3) simplified implementation. In power systems, several controllers have been developed for PSS. One such controller [8] for a small hdyro unit has been undergoing field test in Japan Other systems have been developed for voltage regulators [11] and the control of FACTs devices [12]. Most of these designs have been tuned to a specific system. Unfortunately, such numerical solutions generally require a large computational effort. In this paper, a general design and analysis methodology is proposed. The proposed method also pursues small signal stability analysis which provides the opportunity to design d system with adjustable controller parameters to obtain suitable root location [13].

Although fuzzy logic methods have both a well-founded theoretical basis and numerous successful implementations, controversy has surrounded the developed systems. This is due in part to the lack of satisfying performance measures. Recently, there have been efforts directed at appropriate stability measures for fuzzy *logic* controllers [10,13]. In the power system, performance concerns are particularly acute with the high reliability requirements and the costly effects of instabilities Yet, analysis using precise mathematical models may be infeasible due to the power system complexity (i e , large dimension, non-linearitie s, uncertainties in load fluctuations, disturbances and generator dynamics, and so on). The viewpoint oPered here is that fiizzy logic has been introduced because of the above difficulties and thus, the approach should be better equipped than conventional methods to address these performance concerns In this work, a first step is taken towards systematic analysis. For simulation studies, the non-linear power system and controller are linearized and small signal stability analysis is performed. It is proposed to rethink the traditional methods of stability assessment in terms of greater unceaainties.

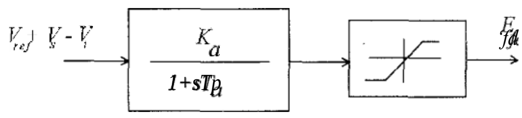


Fig. 2 Excitation System

## 2. SYSTEM MODELS

In this section, the generator and system models are presented (details can be found in the Appendix). The block diagram of the generator plant model is shown in Fig. 1. Specifically, the plant is modeled based on a generator model incorporating single-axis field flux variation and the simple excitation system shown in Fig. 2. The PSS used for comparison studies is a lead compensator. The follov ing continuous transfer function $He_x(s)$ models the exci ation system and regulator:

$$Hq,(s) = \frac{K_a}{I\,sT_a} \quad (1)$$

### 2.1 &o›ver system stabilization

The stabilizing signal is introduced in conjunction with the reference voltage to obtain feedback for the regulator- exciter system. In this study, both a traditional PSS and a fuzzy logic based stabilizer (FPSS) are analyzed. The traditional PSS is modeled by the following transfer function:

$$D(s) = \frac{sK\ T}{1+sT}\left(\frac{1+\ 1}{1+sT_2}\right) \quad (2)$$

The first term in (2) is a reset term that is used to "wash out" the compensation ePect after a time lag $T$. The use of reset control will assure no permanent offset in the terminal voltage due to a prolonged error in frequency, which may

PSS Washout filter

$V_s$

*re * Voltage regulator Excjter chfOTlOllS machine $V_t$

Fñter

Fig. 1 Generator Plant Model

occur in an overload or islanding condition The second term of (2) is a lead compensator to account for the phase lag through the electrical system [14]. In many practiGal cases, the phase lead required is greater than that obtainable from a single lead network In this case, cascaded lead stages are used where k is the number of lead stages.

### 2.2 Fuzzy stabilizer

The development of the fuzzy logic approach here is limited to the controller structure and design. More detailed discussions on fuzzy logic controllers are widely available, e.g., [9,12] For the proposed FPSS, the second term of (2) is replaced with a fuzzy logic rule-base using the filtered speed deviation and acceleration of the machine. That is, the deviation from synchronous speed and acceleration of the machine are the error, e, and error change, $e$, signals, respectively, for the controller. The control output, $u$, is the stabilizing signal K, . Each control rule A; is of the form.

IF e is d 7
AND $\acute{e}$ is $B;$
THEN $u$ is $C,$

where fi „fi, and C, are fuzzy sets with triangular membership functions as shown normalized between -1 and 1 in Fig 3. These same fuzzy sets are used for each variable of interest; only the constant of proportionality is changed. These constants are $K_e$ › é and $K$ for the error, error change and control output, respectively The error and error change are classified according to these fuzzy membership functions modified by an appropriate constant A specific signal may have non-zero membership in more than one set Similarly, a specific control signal may represent the contribution of more than one rule Rule conditions are joined by using the minimum intersection operator so that the resulting membership function for a mle is:

$$yp\,(e, \acute{e}) = \min(pq\ (e), aB,(e)) \quad (3)$$

The suggested control output from rule $i$ is the center of the membership function C, Rules are then combined using the center of gravity method to determine a normalized control output i\7:

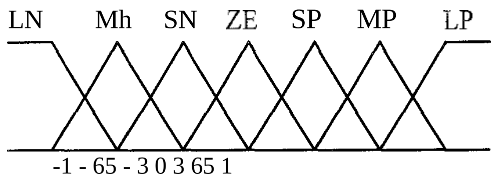


Fig. S. Membership functions scsled from -1 to 1
*(LP− large po.sitive, MP= medium positive,' SP- small positive,• ZF =zero, SN s=mall negative; MN =medium negative, SN =small negative)*

$$U = \frac{\sum_{i=1}^{n} \mu_{R_i}(e;\dot{e}) \cdot U_i}{\sum_{i=1}^{n} \mu_{R_i}(e;\dot{e})}$$

2.3 Proposed FPSS 3esign steps

The fuzzy logic controller development so far is general A particular control design requires specification of all control rules and membership functions. The control rules are designed from an understanding of the desired effect of the controller For example, consider the rule:

IF e is SN
ANB *e* is SP
THEN u is ZE

This rule anticipates that the desired operating point will be reached soon and stabilization control is no longer needed. The complete set of control rules is shown in Table 1. Each of the 49 control mles represents a desired controller response to a particular situation. The control rules were designed to be symmetric under the assumption that if necessary any asymmetries could be best handled through Se aling. In addition, Adjacent regions in the rule table allow only nearest neighbor changes in the control ouput (LN to MN, MN to SN and so on). This ensures that small changes in e and *é* result in small changes in x.

Many of the fuzzy logic controllers proposed in the literature rely on manual tuning of control rules aRd membership functions to establish the desired performance for a specific system. (There are some exceptions, e.g. [15], and iliany authors have proposed artificial neural net methods for tuning the controller). Such manual tuning may be very time consuming and perhaps more impo8antly sheds some doubt on the claims for robustness of the fuzzy logic approach In this work, a systematic tuning methodology is proposed It is assumed that the fundamental control laws change quantitatively not qualitatively with the operating condition. In this vein, control rules and membership functions are designed once as above. The membershi functions are modified by scaling through the constants $K_e$ ›

*e*

| *e* | LN | MN | SN | ZE | SP | MP | LP |
|---|---|---|---|---|---|---|---|
| LN | *LP* | *LP* | *LP* | *MP* | *'MP* | *SP* | *ZE* |
| MN | *LP* | *MP* | *MP* | *MP* | *SP* | *ZE* | *SN* |
| SN | *LP* | *MP* | *SP* | *SP* | *ZE* | *SN* | *MN* |
| ZE | *MP* | *MP* | *SP* | *ZE* | *SN* | *MN* | *MN* |
| SP | *MP* | *SP* | *ZE* | *SN* | *SN* | *MN* | *LN* |
| MP | *SP* | *ZE* | *SN* | *MN* | *MN* | *MN* | *LN* |
| LP | *ZE* | *SN* | *MN* | *MN* | *LN* | *LN* | *LN* |

Table. 1. Rules table
*(Control outputs are italicized)*

e anfl *K* for a particular system and range of operating conditions. The methodology is described below

1. Select the maximum control output for *K* based on the physical limitations of the controller.
2. Replace the FPSS with a constant gain /C.
3 Simulate a significant disturbance until oscillations either begin to settle or the system exceeds the stability limit.
4. se t li e Andh e o the maximum observed values for error e and é, respectively, during the simulation perlod.

If damping appears inadequate then:

5. Linearize the system and FPSS around the nominal operating point (see section 4).
6. Using traditional eigen value analysis, adjust ›r e And li e together (i.e maintaining the same relative magnitude) to obtain desired damping.

As an objective of the fuzzy controller is to manage a wide range of operating conditions and modelling uncertainties, the simulation in step 3 for method 1 may need to be repeated under a set of parameter variations The controller is adaptive in the sense of the varying of these gains but not in terms of varying the control mles. Further discussion on these design steps can be found in [16].

## 3. NUMERICAL SIMULATION

In this section, simulations illustrate the controller response to several disturbances The scenarios are intended to exercise the controller rather than to represent any specific system scenario. Two simple systems are presented but higher order systems have been simulated with similar results The FPSS constants are found by simulations of a

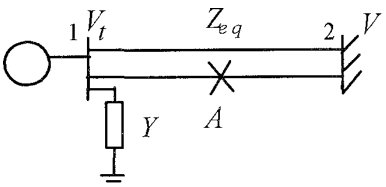


Fig. 4 Single machine connected infinite bus

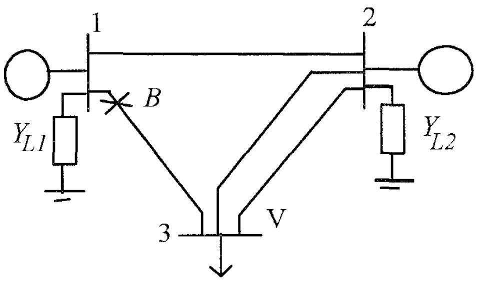


Fig. 5 Two machine - three bus system

step change in mechanical power input using the non-linear model of Appendix A. The PSS is designed using a conventional phase lead technique to precisely compensate for the phase lag of the electrical loop Two systems are used for the simulations. A single machine connected to an infinite bus, adapted from [17], was used in the design phase and then this controller was used for studies of a multi-machine system, adapted from [18]

3.1 Single machine

The single machine connected to an infinite bus shown in Fig. 4 has the following system parameters

Generator: â7—9.26s, D= 01 p u, 'd! 7 76 s. d .973 p.u, X'd=190 p u.
Voltage regulator : $K_A$ 50, $T_A$ .05 s, \E fd\ S 10
Network *(Note. The negative R arises from modelling external equivalent of generation.)* Y— 0.6 +y0 3, K—1.05; both lines A=0.68, I—1.994;
Power system stabilizer: K,=7.09, T—3 0s, *Th* 0.6851s, *Th*=3 1s
FPSS•' e = 40.0 / e = 9.25 /? 1.0 =
Mechanical input power $P_m$=1

Two cases were simulated and are shown in the figures on the following page

* Case 1: Step change of mechanical power from *Pp i* = to $P_m$ 1.3 p u. The plots show frequency and rotor angle response to this disturbance for systems with the PSS and the FPSS design (see Fig. 6)

+ Case 2: Three phase to ground fault at *A* (Fault is 30% of the distance along line) Line is removed with a fault clearing time r,=0 2 sec The plots show the response of the systems with the PSS and the FPSS design (see Fig. 7)

3.2 Multimachine

A system with two machines connected to an infinite bus is shown in Fig 5 The system has the following parameters (all values in per unit)'.

Network: line 1-2 A=.018, I=.11, *B* .226; both lines 2-3 A=008, I= 05, & .098; line 1-3 *R* 007, I= 04 *B* .082; =
? =0.6-JO.3, $Y_2$ 0.8-J'0.2
Mechanical power: =1.2, *!°m2*

Generator parameters are the same as in the single machine case. One scenario is presented here:

* Case 3: Three phase to ground fault at *B.* (Fault is 30% of the distance along line 1-3). The line returns to service with clearing time r,=0 15 sec (Fig. 8). Plots show response for systems with the PSS and ie FPSS design.

3.3 Discussion

In all cases, the FPSS shows superior or similar response to the traditional controller. For smaller disturbances, the improved damping is not as noticeable For the more severe disturbances, the FPSS controller has signiCicantly better performance. The multi-machine simulations demonstrates the controller robustness in that the controller remains effective despite significant changes in the system dynamics

## 4. PERFORMS.NCE ANALYSIS

4.*i* Small signal stability

For small dismrbances, stability can be characterized by the system linearized about the operating point If the eigenvalues of this system lie in the leñ hand plane, the system is small disturbance stable In this study, the delay caused by computation is neglected so that the fuzzy logic controller can be modeled as a zero memory non-linearity This is a reasonable assumption as the rotor oscillations of interest are orders of magnitude slower than the time required for the FPSS computations. The FPSS does not introduce new poles but acts to shiñ the eigen values of the uncompensated system.

A difficulty of the small signal analysis lies in the fact that the FPSS is not differentiable. This problem is managed by numerically calculating a linear approximation near the operating point. Table 2 shows the eigenvalues for the system with the traditional PSS and the FPSS design As the FPSS should provide proper stabilization control over a wide range of operating conditions, the eigenvalues are found at two operating points. The system is designed for the nominal operating point and the eigenvalues are recalculated at the second operating point without changing the controller parameters While the uncompensated system has two eigenvalues in the right hand plane, both the traditional PSS and FPSS act to move the eigenvalues into lefl hand plane and establish small disturbance stability. It is interesting to note that the FPSS shows good small signal performance with relative insensitivity to the operating point Similar results were found for the multimachine system.

4.2 Transient stability

For large disturbances, the system non-linearities must be considered It is possible to apply Lyapunov functions to

| Operating | PSS | FPSS |
|---|---|---|
| Nominal<br>$P_m$=1 | - 1.361 ± J4.452<br>- 4.290 ± J8.199<br>- 18.88<br>- 0.33 | * 2.072 ± J3.235<br>- 8.027 ± J13.312<br>- 0 33 |
| $P_m$= 1.30 | - 0.818 ± /3.727<br>- 8 814 ± /8.703<br>- 19.?i9<br>- 0.33 | - 1.790 ± /2.634<br>- 8.309 ± /14.412<br>- 0.33 |

Table 2: Eigenvalues for the single machine systems

| Operating Point | PSS | FPSS |
|---|---|---|
| *Single machine* | | |
| Nominal | 0.53 sec. | 0.84 sec. |
| P,—1.30 | 0 0Ë SCG. | 0.14 sec. |
| *Two machine* | | |
| Nominal | 0.25 sec. | 0. 31 sec. |
| *Pp* —1.2, P$_{AQ}$—1.0 | 0,23 SoC. | 0.28 sec. |
| /',,——1.2, P——1.2 | 0.21 sec. | 0 24 sec. |

Table 3: Critical clearing times for example systems

fuzzy logic controllers but our results in this area are still preliminary A numerical approach is pursued here The critical clearing time tCCT) is calculated for a number of operating points for the PSS and FPSS systems The results are shown in Table 3 In all cases, the FPSS designs improve the margin of stability as indicated by the CCT.

## 5. CONCLUSIONS AND DISCUSSION

This paper proposes a general structure for a fuzzy logic stabilizer. Controller design requires calculation of ihe maximum ranges for frequency and frequency deviation during some specified disturbance. The advantage of this design approach is that the controller is insensitive to the precise dynamics of the system Simulation of the response to disturbances has demonstrated the effectiveness of this design technique. Small signal and transient stability analysis give some evidence of the robustness of the controller

This research is directed at developing systematic methods of design and analysis for fuzzj/ logic based stabilization control. The ability to design controllers which are effective under extreme uncertainty of dynamic model parameters is felt to be of growing relevance as the number of energy suppliers connected to the network increases

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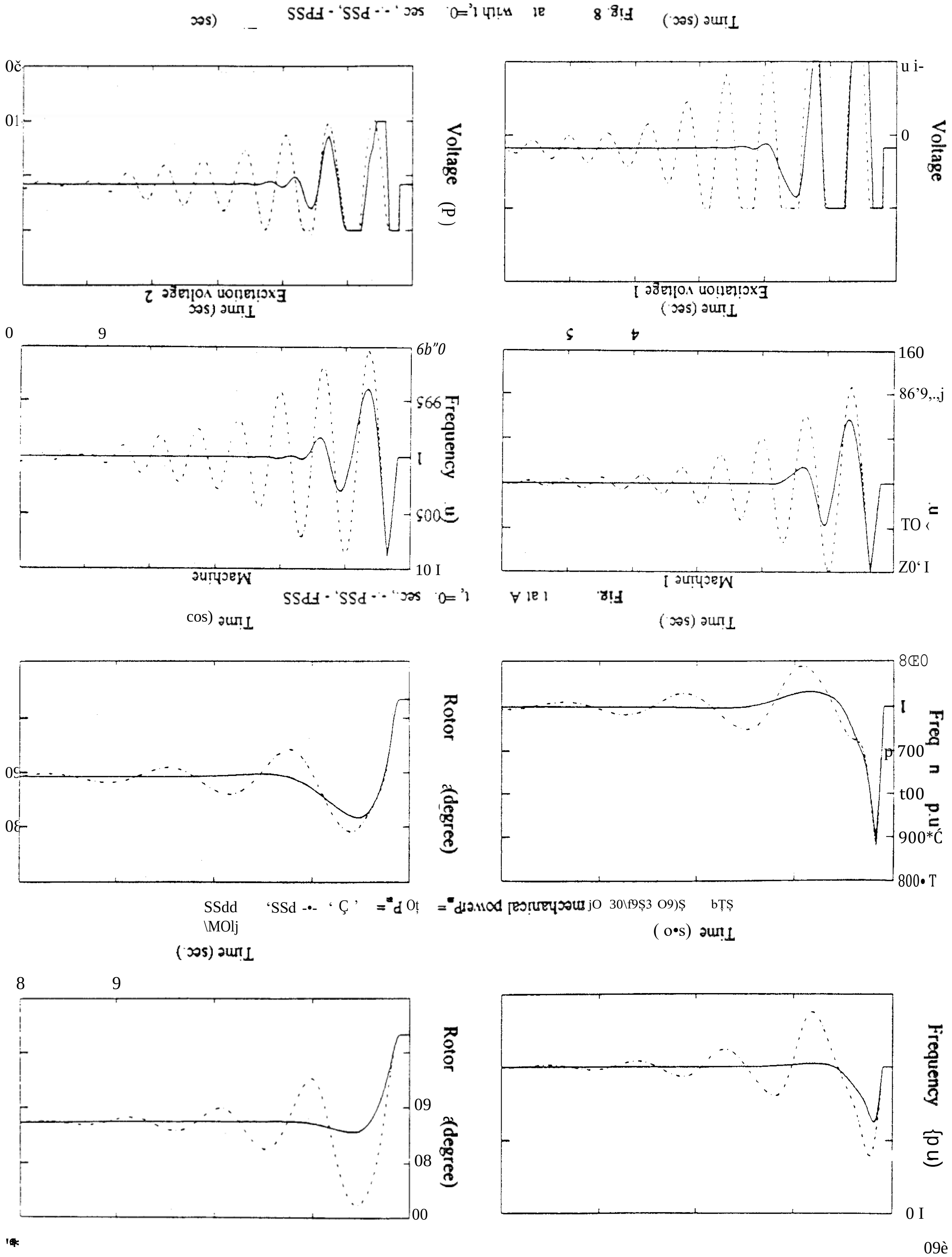

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## APPENDIX A: DETAIL MODELING

The study systems are described by the following diPerential and algebraic equations:

$$\delta_i \quad \omega_i - \omega_{ref} \qquad \text{(B-1)}$$

$$\omega_i \quad (-D_i \cdot (\omega_i \quad \omega_{ref}) + P_{m_i} \quad P_{G_i})/M_i \qquad \text{(B-2)}$$

$$\dot{E}'_{q_i} \quad (-E'_{q_i} - (X_{d_i} \quad X'_{d_i}) \cdot I_{d_i} + E_{fd_i})/T_{d0_i} \qquad \textit{(B-3)}$$

$$\text{(B-4)} \quad P_{G_i} \quad V_{d_i} I_{d_i} + V_{q_i} I_{q_i}$$

$$\text{(B-5)} \quad Qc_i = V_{q_i} I_{d_i} - V_{d_i} I_{q_i}$$

$$I_{d_i} - (E'_{q_i} \quad V_{q_i})/X'_{d_i} \qquad \text{(B-6)}$$

$$I_{q_i} \quad (E'_{d_i} \quad V_{d_i})/X'_{q_i} \qquad \text{(B-7)}$$

$$V_{d_i} - V_i \sin(\delta_i \quad \alpha_i) \qquad \text{(B-8)}$$

$$V_{q_i} - V_i \cos(\delta_i - \alpha_i) \qquad \text{(B-9)}$$

$$P_{G_i} \quad P_{L_i} \quad \sum_{j=1}^{n} V_i V_j Y_{ij} \cos(\alpha_i \quad \alpha_j \quad \gamma_{ij}) \qquad \text{(B-10)}$$

$$Q \quad -Q_{L_i} \quad \sum_{j=1} V_i V_j Y_{ij} \sin(\alpha_i \quad \alpha_j \quad \gamma_{ij}) \qquad \text{(B-11)}$$

$$E_{fd} = \{-E_{fd} \quad K_a \quad "ref + \quad s - \quad \} T \qquad \text{(B-12)}$$

where

$\delta$ Generator rotor angle
$\omega$ Synchronous frequency
$E\$$ Internal quadrature axis voltage
$E_d$ Internal direct axis voltage
$V_d$ Direct axis voltage
$V_q$ Quadrature axis voltage
L Terminal voltage
D Damping factor
$P_m$ Mechanical power input
$P_G$ Generator real power
$L$ Load real power
$Qc$ Generator reactive power
$Q_L$ Load reactive power
Id Direct axis current
M Moment of inertia
$X_d$ Direct axis reactance
$X_q$ Quadrature axis reactance
$X'_d$ Direct axis transient reactance
$X'_q$ Quadrature axis transient reactance
Efd Field voltage
n Number of generators
Y Y bus matrix
$\gamma$ Angle of Y bus matrix
ref Reference voltage
y, Stabilizing input signal
K Regulator amplifier gain
T, Regulator amplifier time constant