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A Robust Controller Design for a Multimachine Power System

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Introduction

Many pole-placing control methods have been used before by investigators for the purpose of controlling effectively and significantly enhancing the dynamic stability characteristics of large synchronous generators operating in practical power systems. Usually, these methods are based on "optimal control strategies» [1] or on "algebraic control strategies" [2]. In recent years, there has been considerable interest in the application of control techniques to design excitation controllers for synchronous generators. The excitation controller can be employed to control synchronous generators and achieve considerable improvement in system dynamic stability [3-5].

One of the most used techniques for algebraic control strategies is the model-reduction approach. The model reduction methods may be applied directly to either state-space model formulations of systems or to transfer function model formulations. A general order - reduction method [6], using appropriate dominant pole - selection criteria, suitable for application to a high - order linear, time invariant systems to obtain adequate low - order models has been applied successfully in the present work. In this paper the robust excitation control of a synchronous generator in a multimachine power system is applied using the above model reduction method.

This paper is concerned with the systematic evaluation of a proposed robust excitation controller which is applied to a generator of a multimachine power system. The evaluation involves a detailed multimachine power system model and the determination of the excitation controller model of the controlled synchronous generator.

The linearized mathematical model of the multimachine power system contains detailed representation of the steam–turbine generators, excitation and speed governor systems, transmission networks, power transformers, induction motors and static loads, in phase coordinate representation (i.e. in *abc* phase coordinate system). The excitation controller is arrived at: by using the developed high-order linearized model of the controlled generator in *dqo* coordinates, which in turn is reduced (using an *elegand* order reduction method [6]) to a low-order model with certain retained eigenvalues and measurable state variables. Based on the low-order model and the application of a pole-placing algebraic control method the feedback gains of the associated closed-loop system are computed. This is repeated for a number of machine P and Q loading combinations which leads to the creation of a computer program file called ADAPT, which contains the considered machine loading and the computed respective feedback gains of the so designed controllers for the reduced-order machine model. Finally the created ADAPT file is properly integrated in the *abc* coordinate linearized model of the controlled generator of the multimachine system for providing the desired excitation control.

The resulting robust excitation controller is evaluated in the multimachine power system context by comparing its behaviour with the corresponding one of conventional AVRs under symmetrical and unsymmetrical faults applied to the system model, in order to justify its suitability for use in a multimachine power system.

Proposed robust excitation control method [5]

In order to formulate the problem of multimachine controller design, using algebraic control theory, a set of state variables must be first selected. Then the state equation for the dynamical open - loop power system model is written in the vector - matrix differential equation form

$$\begin{cases} \dot{x} = Ax + bu, \\ y = Cx, \end{cases} \tag{1}$$

where $x \in R^n$, $u \in R^m$ with $m < n$, $y \in R^p$ with $p < n$, and A, B, C are constant system matrices with appropriate dimensions. The system defined by eq. (1) have distinct real and/or complex pairs of poles (eigenvalues) $\lambda_1, \lambda_2, \cdots \lambda_n$ (written in decreasing order of dominance: where the damping of some of them may not be satisfactory) and their characteristic polynomial is:

$$P(s) = p_0 + p_1 s + ... + p_{n-1} s^{n-1} + s^n . \tag{2}$$

The pole-displacement problem with output - feedback is to find an mxp constant gain - feedback matrix K of the output - feedback control low

$$u = -K^T y + u_0 = -\left[K^T \; 0\right] x + u_0 , \tag{3}$$

where $u_0 \in R^m$ is the new control input vector.

Such that the resulting closed - loop system

$$\begin{cases} \dot{x} = \left(A - BK^T\right)x + Bu_0 = \hat{A}x + Bu_0, \\ y = Cx \end{cases} \qquad (4)$$

has some of its poles pre-assigned (or approximated to desired values), e.g. p poles $\overset{\frown}{\lambda}_1, \overset{\frown}{\lambda}_2, \cdots \overset{\frown}{\lambda}_p$ the remaining ones $(\overset{\frown}{\lambda}_{p+1}, \overset{\frown}{\lambda}_{p+2}, \cdots \overset{\frown}{\lambda}_n)$ being free to be located automatically.

The characteristic polynomial of the system of eq. (4) is

$$\hat{P}(s) = \hat{p}_0 + \hat{p}_1 s + ... + \hat{p}_{n-1} s^{n-1} + s^n . \qquad (5)$$

Assuming that the gain - feedback matrix K^T is a dyadic product of p and q^T, then the multi - input system of eq. (1) is converted to a single - input system (A, b),. where

$$p = [p_1, p_2 ....p_m]^T$$

and

$$b = [B_p] = [b_1, b_2, ...b_n]^T$$

and

$$K^T = pq^T . \qquad (6)$$

The task now becomes to find the gain - feedback vector q^T of the control low for the obtained single - input multiple - output system.

The desired state gain feedback vector f^T is given by

$$f^T = [\hat{p} \quad 1]E , \qquad (7)$$

where

$$\hat{p} = [\hat{p}_0, \hat{p}_1 ...., \hat{p}_{n-1}]^T$$

and

$$E = [e, A^T e, ..., (A^n)^T e]^T .$$

The e^T is the last row of the inverse controllability matrix S^{-1} (i.e. $|S| \neq 0$), where

$$S = \left[b \vdots Ab \vdots A^2 b \vdots \cdots \vdots A^{n-1} b\right]. \qquad (8)$$

For output feedback, g of the gains of the feedback vector are fixed and thus $n - g$ are free, then the characteristic polynomial of the closed loop system can be expressed in factored form as follows

$$\hat{P}(s) = Q(s) \cdot R(s) , \qquad (9)$$

where $Q(s)$ is the assignable part of the polynomial and $R(s)$ is its residual part.

The coefficients of the product polynomial can be written as

$$\begin{cases} [\hat{p}^T \quad 1] = [r^T \, 1] \cdot Q = [r^T \, 1] \cdot \begin{bmatrix} \dfrac{D}{d^T} \end{bmatrix}, \\ [p^T \, 1] = [r^T \, 1] Q = [r^t \, 1], \end{cases} \qquad (10)$$

where

$$\begin{bmatrix} \dfrac{D}{d^T} \end{bmatrix} = \begin{bmatrix} q_0 & q_1 & \cdots & q_{n-g-1} & 1 & 0 & \cdots & 0 \\ 0 & q_0 & \cdots & \cdots & q_{n-g-1} & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \cdots & \vdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \vdots \\ 0 & 0 & \cdots & \cdots & \cdots & q_{n-g-1} & \cdots & 1 \end{bmatrix} . \qquad (11)$$

Defining f_a as the free gains and f_b as the fixed gains, then

$$f^T = \left[f_a^T \vdots f_b^T\right] = \left[\hat{p}^T 1\right] \cdot \left[E_a \vdots E_b\right] = \left[r^T 1\right] \cdot \begin{bmatrix} \dfrac{D}{d^T} \end{bmatrix} \cdot \left[E_a \vdots E_b\right], \qquad (12)$$

which, after the mathematical manipulations, gives

$$r^T = \left(f_b^T - d^T E_b\right) \cdot \left(DE_b\right)^{-1} \qquad (13)$$

and

$$f_a^T = \left(r^T D + d^T\right) E_a . \qquad (14)$$

Based to the above procedure the gain – feedback vector q^T of eq. (6) given by

$$q^T = f_a^T . \qquad (15)$$

Now, since $K^T = pq^T = pf_a^T$, the closed loop system of eq. (4) is completely determined.

A practical problem still remains as how to select the values of the elements of vector p. Their choice is very much arbitrary and the best guide is intuition and trial and error approach.

Case under study

The complete multimachine system under study is shown in Fig. 1. The complete data of the system are shown in [3].

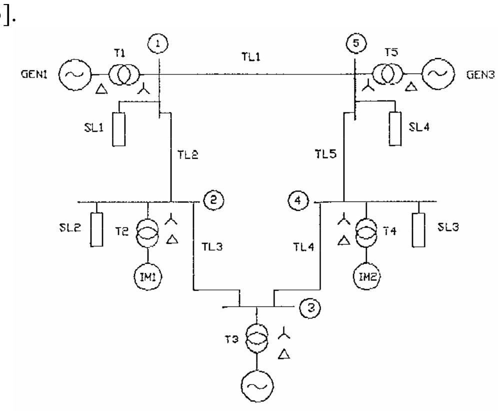

Fig. 1. Multimachine power system under study

Each synchronous generator unit is represented in phase coordinates with an 8th-order linearized model [7] which includes the 2nd-order swing equation. Its excitation control system is a 5th-order standardized IEEE model [8], whereas its steam -turbine is a three-stage type with reheat representation and is modelled by a 5th-order linearized model (including the speed governing system) [9]. Each induction motor of the system drives a pump load and the complete dynamic load is represented in phase coordinates by an 8th-order linearized model [10]. On the other hand, each static load is represented in phase coordinates by a 3rd-order linearized model [11, 12].

Finally, each power transformer is represented in phase coordinates by a 6th-order linearized model [10, 11], whereas each transmission line network is represented in phase coordinates by a typical π-section model [11-13].

Simulation results

The overall special digital computer program developed based on the system configuration of Fig. 1 and the pertinent control theory of paragraph 2.

The excitation controller designed was applied to control the steam synchronous generator with its classical IEEE Type-2 controller (GEN1) of the multimachine power system of Fig. 1. The other two generators of the system have IEEE Type-2 excitation systems, while the three turbines are controlled with conventional speed governors. For purposes of comparison similar results were obtained with the GEN1 being controlled only with its 5th-order IEEE Type-2 excitation control system, i.e., without the excitation controller.

The transient performance of the overall system, was obtained through the use of the computer program for the above two cases (without and with the excitation controller) and for a three-phase symmetrical fault being applied at node 2 of Fig. 1 four seconds after the simulation start and it last for 150 msec, after which the fault is cleared. The respective time responses of the output variables of the controlled generator (GEN1), i.e. v_t, δ, are shown in Fig. 2.

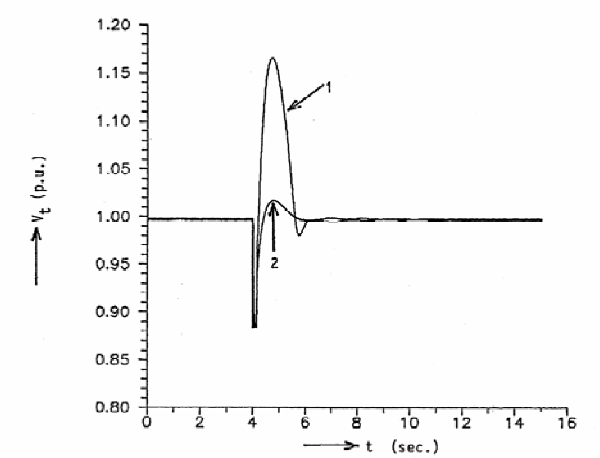

Fig. 2(a). Output time responses (v_t) of GEN1 for 3 - Phase fault at node 2: 1 – GEN1 with IEEE Type-2 excitation control; 2 – GEN1 also with designed excitation controller

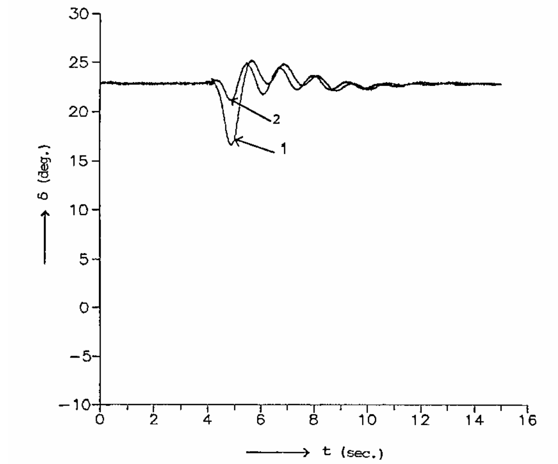

Fig. 2(b). Output time responses (δ) of GEN1 for 3- Phase fault at node 2: 1– GEN1 with IEEE Type-2 excitation control; 2 – GEN1 also with designed excitation controller

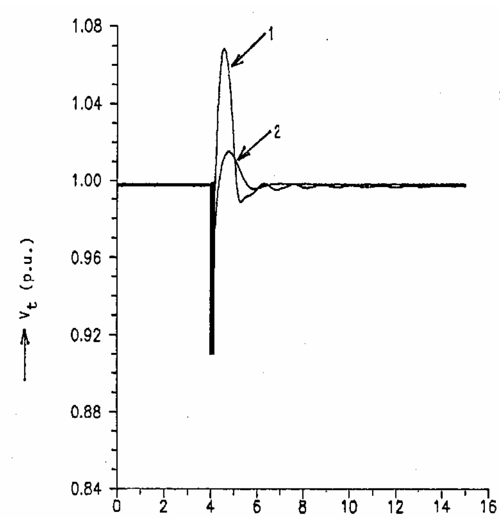

Fig. 3(a). Output time responses (v_t) of GEN1 for Single-phase earthed fault at node 2: 1 – GEN1 with IEEE Type-2 excitation control; 2 – GEN1 also with designed excitation controller

These results show clearly that the use of the robust excitation controller (designed in the sense of this work) in the multimachine power system leads to more stable and better damped responses by comparison to the ones without the excitation controller. The last observation-conclusion may be altered (weakened) to some extent if the parameters of the conventional excitation controller are chosen in an optimal way.

Similar results were obtained with the use of the computer program while applying unsymmetrical faults a) Single-phase earthed fault, b) Phase- to phase earthed fault and c) Phase – to phase short circuit fault, to node 2 of Fig 1, in a manner similar to that applied in the three-phase fault case, and the time responses of the same output variables are shown in Fig. 3, Fig. 4 and Fig. 5 respectively. These results also show that the introduction of the excitation controller in the multimachine power system yielded pronounced improvement in the dynamic stability characteristics of the controlled generator (GEN1).

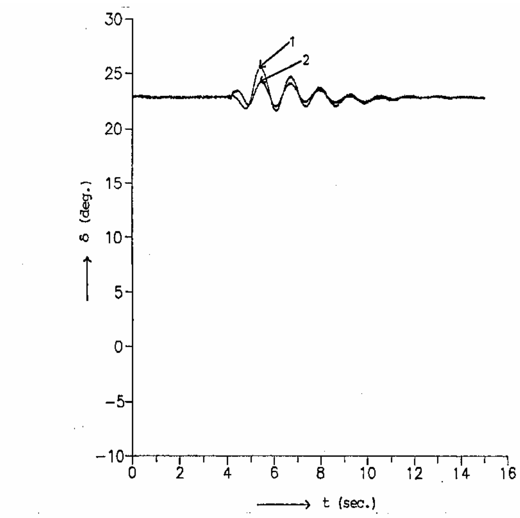

Fig. 3(b). Output time responses (δ) of GEN1 for Single-phase earthed fault at node 2: 1 – GEN1 with IEEE Type-2 excitation control; 2 – GEN1 also with designed excitation controller

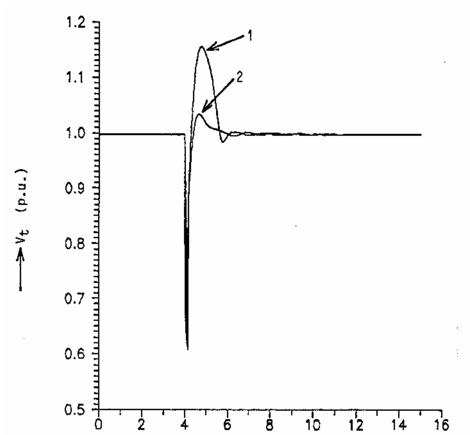

Fig. 4(a). Output time responses (v_t) of GEN1 for phase to phase earthed fault at node 2: 1 – GEN1 with IEEE Type-2 excitation control; 2 – GEN1 also with designed excitation controller

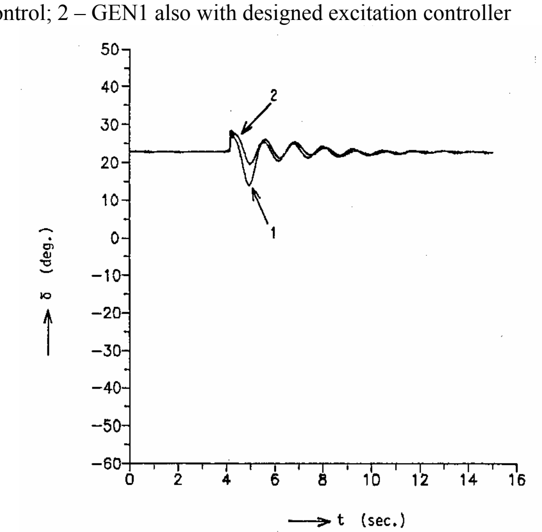

Fig. 4(b). Output time responses (δ) of GEN1 for phase to phase earthed fault at node 2: 1 – GEN1 with IEEE Type-2 excitation control; 2 – GEN1 also with designed excitation controller

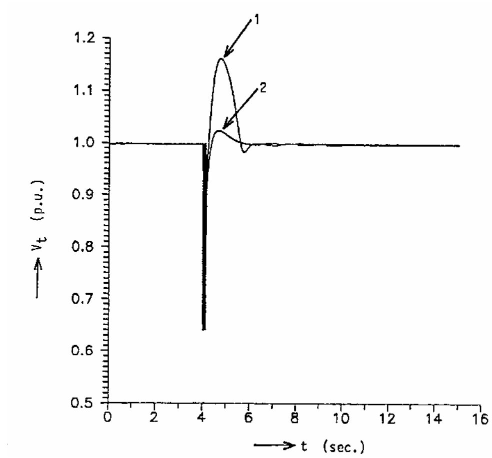

Fig. 5(a). Output time responses (v_t) of GEN1 for phase to phase short-circuit fault at node 2: 1 – GEN1 with IEEE Type-2 excitation control; 2 – GEN1 also with designed excitation controller

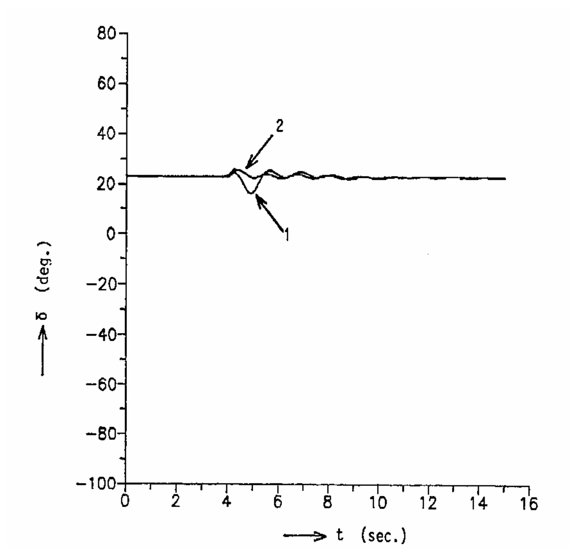

Fig. 5(b). Output time responses (δ) of GEN1 for phase to phase short-circuit fault at node 2: 1 – GEN1 with IEEE Type-2 excitation control; 2 – GEN1 also with designed excitation controller

Conclusions

The paper presents the design and application of a robust excitation controller based on a simulated multimachine power system. The control strategy is based on a previously established algebraic control method which is applied to multimachine power system environment. The designed excitation controller proved its goodness for a wide range of load conditions of the controlled generator and thus its robustness was established.

The results obtained were based on a detailed multimachine model in phase coordinates containing steam turbine synchronous generator units, excitation and turbine-governor systems, transmission networks, power transformers, induction motors and static loads. These results show that the proposed excitation controller integrates smoothly and performs satisfactory in a multimachine power system environment under symmetrical and unsymmetrical fault conditions, operating in parallel with the conventional AVRs of the other units of the power system.

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Note:

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D. Bandekas, G. Tsirigotis, P. Antoniadis, N. Vordos. Daugiamotorių galios sistemų valdiklių projektavimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2006. – No. 1(65). – P. 20–24.

Aprašomos daugiavariklės galios sistemos, kuriom valdyti panaudojami grįžtamųjų ryšių sinchroniniai generatoriai. Įrodyta, kad šį reiškinį galima naudoti ir tuo atveju, kai valdoma kitų sistemų generatoriais. Pasiūlytas metodas pasižymi sudėtingų sistemų valdymo ir jų taikymo praktiniams uždaviniams spręsti paprastumu. Il. 5, bibl. 13 (anglų kalba; santraukos lietuvių, anglų ir rusų k.).

D. Bandekas, G. Tsirigotis, P. Antoniadis, N. Vordos. A Robust Controller Design for a Multimachine Power System // Electronics and Electrical Engineering. – Kaunas: Technologija, 2006. – No. 1(65). – P. 20–24.

An excitation control method using state feedback is applied to a synchronous generator in a multimachine power system, while a phase to earth unsymmetrical fault or a three-phase symmetrical fault being applied. The simulation results of the study show that the excitation controller performs satisfactorily in a multimachine environment, when operating in conjunction with the conventional regulators of the other system generators. The proposed method for designing implementable robust excitation controllers is relatively simple to apply. Ill. 5, bibl. 13 (in English; summaries in Lithuanian, English and Russian).

Д. Бандекас, Г. Тсириготис, П. Антониадис, Н. Вордос. Проектирование устройств управления многомоторных систем мощности // Электроника и электротехника. – Каунас: Технология, 2006. – № 1(65). – С. 20–25.

Описываются многомоторные системы мощности, в которых применяются в качестве обратной связи синхронизированные генераторы. Показано, что результаты исследования полностью подтверждают возможности использования контрольных устройств, когда управление осуществляется генераторами других систем. Предложенный метод отличается простотою их управления и применения. Ил. 5, библ. 13 (на английском языке; рефераты на литовском, английском и русском яз.).

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