CONTROL AND STABILITY ANALYSIS OF A SUPERCONDUCTING GENERATOR IN A MULTI-MACHINE POWER SYSTEM

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ABSTRACT

The paper describes a frquency domain technique for the controller design and stability analysis of multi-machine power system including a superconducting genertor (SCG). An equivalent model for each generator is obtained, taking into account the dynamic interaction between units, and is used as a base for controller design, the air-cored nature of the SCG and its very long field time constant renders that the governor control is to be considered only. The design technique enables the controller designers to add the required phase at the machine electromechanical frequency, ensuring a satisfactory transient response and prevent the possibilities of system failure.

1. INTRODUCTION

The continuous increase in demand for electrical power renders to install large generating units. Generating units of ratings greater than 1000 MW are now in service, and sizes of 2000 MW output have been considered as an economical size [1]. It has been revealed that the design parameters of such large conventional machines, high p.u. reactance and low inertia constant, reduces the stability margin and adversly affect the system performance [2]. A possible way of overcoming these problems would be by developing superconducting

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machines, which are expected to have higher efficiency, smaller size and weight, improved system stability and possible generation at bus voltages. Most of the literatures are related to the design and field analysis of the new machine [3-5].

Control of SCG when synchronized into power networks represents an interesting area. This due to that the new machine have a different construction criterion to that of the conventional synchronous machines. The SCG has almost zero resistance of the field winding (the field winding time constant is about 750S.). So, excitation control, which is very effective in conventional generators, becomes ineffective in improving the dynamic performance of the SCGs.

Therefore, the governor control is considered as the only available loop. Publications regarding the control of a single machine connected to an infinite bus bar consideres only this loop [6,7]. Moreover, examination of the influence of the introduction of a SCG into a system with conventional generators has already bean documented [8].

This paper presents a technique for obtaining an equivalent frequency domain model for SCG in a multi-machine power system and uses this model as a base for controller design. A multi-stage phase advance network is designed, for the governor control loop, to ensure satifactory transient response and to prevent the possibilities of system failure.

2. MULTI-MACHINE SYSTEM STUDIED

The system considered in this study is shown in Fig.(1). It includes three generation busbars. A 552 MVA thermal unit is connected to busbar 1, a 231.6 MVA hydro-electric unit is connected to busbar 2 and a 500 MVA SCG to busbar 3. These generating units are

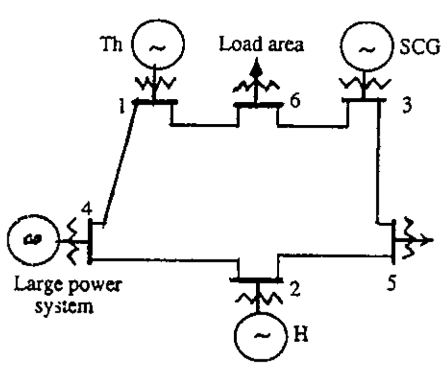

Fig.(1) : System studied

connected to a large power system (bus 4) and load areas (buses 5,6). the transmission network and the loads are represented by lumped impedances, the parameters of the conventional generting units are calculated from manufacturer's data [9]. Due to the air-cored nature of the SCG and the pronounced effect of the end windings, parameters which were obtained based on three-dimensional field analysis have been used in this study [3]. The p.u. values of these parameters based upon individual unit rating are given in Appendix-A.

3. FREQUENCY DOMAIN MODEL

3.1 Generator

Generally low order mathematical model are used to represent generating units in simulating and analyzing large power system. However, in the case under consideration the machines and their controllers are represented in detail. This is necessary for accurate prediction of both the performance of the new machine and the effects of the fast-acting controllers.

Modelling of the conventional synchronous machines followed the traditional d-q Park's representation. However, the doubly screened superconducting alternator is represented by the standard equations of synchronous machines in d-q axes model taking into consideration that each screen is represented by one lumped coil of fixed parameters in each axes. Starting from the well known Park's representation the following equations are obtained for the ith generator [7-9]:

$$\Delta V^i_d+(P/\omega_o)\,\psi^i_{qo}\,\Delta\delta^i + (R^i_a+(P/\omega_o)\,X^i_d(p))\,\Delta I^i_d - X^i_q(p)\,\Delta I^i_q - (P/\omega_o)\,G^i(p)\,\Delta E^i_f = 0 \qquad (1)$$

$$\Delta V^i_q+(P/\omega_o)\,\psi^i_{do}\,\Delta\delta^i + (R^i_a+(P/\omega_o)\,X^i_q(p))\,\Delta I^i_q - X^i_d(p)\,\Delta I^i_d - (P/\omega_o)\,G^i(p)\,\Delta E^i_f = 0 \qquad (2)$$

$$(P^2 M^i + Pk^i_d - PG^i_t)\,\Delta\delta^i - 0\,(I^i_{qo}\,X^i_d(p) + \psi^i_{qo})\,\Delta I^i_d + (\psi^i_{do} + I^i_{do}\,X^i_q(p))\,\Delta I^i_q + I^i_{qo}\,G^i(p)\,\Delta E^i_f = 0 \qquad (3)$$

where, $X_d(p)$, $X_q(p)$ and $G(p)$ are operational impedance and admittance respectively, for conventional machines they are documented in [10] while for superconducting machine they contains parameters of the two damper circuits (screens) in d and q axes [7].

3.2 Excitation System

Typical excitation systems have been used with the conventional generators (thyristor exciters are used with thermal machine and IEEE type-1 is used for hydraulic machine), the perturbed transfer function may be written as [10].

$$\Delta E^i_f = -G^i_E \, \Delta V^i_t + (G^i_E \, G^i_{PSS}) \, P\Delta^{\,i} \tag{4}$$

where, G_E: Exciter/AVR transfer function

G_{PSS}: PSS transfer function.

(Excitation transfer functions and parameters are illustrated in Appendices (A) and (B).

The normal load excitation requirements of the SCG are very small, i.e., 1000 A. at 5 Volts for 1200 MVA superconducting generator. A thyristor controlled static excitation system for the use with large SCG has been designed, whose harmonic content is low so as to avoid appreciable heating in the superconductors [5]. The excitation system transfer function for the superconducting generator is [7]:

$$\Delta E_{f\,sc} = G_{E\,sc} \, [(V_{do}/V_{to}) \; \Delta V_d + (V_{qo}/V_{to}) \, \Delta V_q] \tag{5}$$

where, $G_{E\,sc} = K_{asc} / (1+Pt_{asc})$

3.3 Turbine and Governor System

For conventional machines the turbine and governor models are based on the IEEE representation [11]. The perturbed transfer function may be written as follows for the ith machine [10]:

$$\Delta T^i_M = G^i_t \; \Delta W^i \tag{6}$$

where, G^i_t is the governing system transfer function which depends on the machine type. (Turbine and governor system transfer functions and parameters are illustrated in Appendices (A) and (B).

However, it has been revealed that the turbine system that derives superconducting alternators should be of fast response with fast valving routine [6]. This would certainly may aid to maintain and improve the stability of that low inertia unit. The block diagram representation of the governing system used is shown in Fig.2. Including the phase advance network.

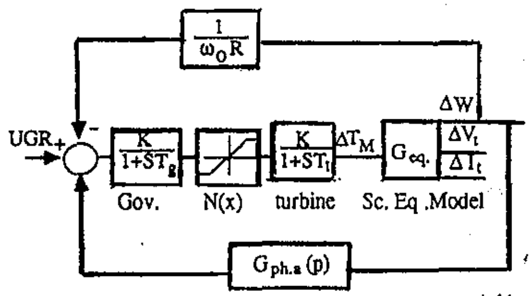

Fig.(2): The governor control system

3.4 Network Representation

The network equations are solved in a common reference frame (D-Q axes), while the individual generator equations are solved in its Park's reference frame (d-q axes). The voltage components of the generator and the network are related to each other as:

$$V^i_{DQ} = T^i \quad V^i_{dq} \tag{7}$$

where for the node to which the ith generator is connected:

$$[T^i] = \begin{bmatrix} \cos \delta^i & -\sin \delta^i \\ \sin \delta^1 & \cos \delta^i \end{bmatrix} \tag{8}$$

Following the procedures of Ref. [10], the following equation may be obtained for the network:

$$[\Delta I_m] = [Y_m] [\Delta V_m] + [K] [\Delta\delta] \tag{9}$$

where:

$$[Y_m] = [T]^t [Y_N] [T]$$

$$[K] = [T]^t [Y_N] [I] + [J]$$

For machine i:

$$[I^i] = \begin{bmatrix} -V^i_d \sin \delta^i - V^i_q \cos \delta^i \\ V^i_d \cos \delta^i - V^i_q \sin \delta^i \end{bmatrix}, [J^i] = \begin{bmatrix} I^i_q \\ -I^i_d \end{bmatrix}$$

3.5 Equivalent Frequency Domain Model

The overall multi-machine system model in frequency domain can be obtained by arranging Eqs. (1)-(3),(4) and (9) for conventional machines or by arranging Eqs. (1)-(3),(6) and (9) for superconducting machine. Dividing all system variables by ΔE^{i}_{f} when the equivalent model concerned any ith conventional unit, or dividing by ΔT_M when the equivalent model concerned the SCG. With the aid of matrix elimination technique the variables not of interest may be eliminated. So, the equivalent model will be:

$$[A_{eq}]\ [\Delta X] = [B] \tag{10}$$

where,

for conventional units

$$[\Delta X]^t = [\Delta V_d/\Delta E_f\,,\ \Delta V_q/\Delta E_f\,,\ \Delta\delta/\Delta E_f\,,\ \Delta I_d/\Delta E_f\,,\ \Delta I_q/\Delta E_f]$$

for superconducting unit,

$$[\Delta X]^t = [\Delta V_d/\Delta T_M\,,\ \Delta V_q/\Delta T_M\,,\ \Delta\delta/\Delta T_M\,,\ \Delta I_d/\Delta T_M\,,\ \Delta I_q/\Delta T_M]$$

4. CONTROLLER DESIGN

The objectives of this part is to use the equivalent model as a base for designing an appropriate controllers to improve the system stability and ensure good transient response. The controllers for conventional machines are basically in electrical loop, automatic voltage regulators and power system stabilizers [10]. However, for SCG it has been revealed that any additional damping may only consider the governor loop (the field winding time constant is about 750 S., so excitation control becomes ineffective). Previous trials considered the design of a phase advance network to substitute for the low inherent damping of a single SCG connected to an infinite bus [6,7].

The design technique was firstly applied on conventional synchronous generators [10], and also on single SCG connected to an infinite bus [7]. The advantages of this technique is its capability to introduce the required phase at the system resonance frequency, this is a very improtant and remarkable point as such design prevents sustained oscillation and consequently system failure.

i- For conventional machines the block diagram shown in Fig. (3) is used to design the required control circuits. From polar plot of $\Delta W/\Delta E_f$, the resonance frequency and the phase required are claculated. Then, the n casade phase lead networks (G_{PSS}) which obtain the required phase at the resonance frequency has a transfer function of:

$$G_{PSS}(p) = K_{PSS}\left((1+\alpha TP)/1+TP\right)^n \quad , \quad \alpha > 1 \qquad (11)$$

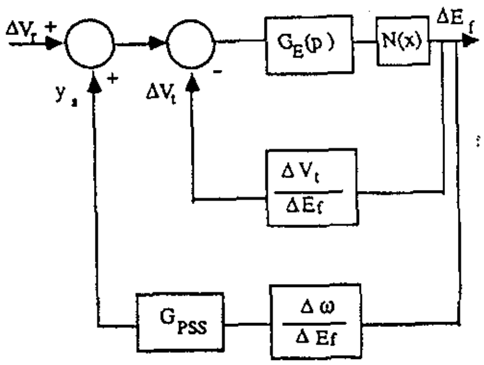

Fig.(3) Block diagram representation used for conventional M/CS controller design

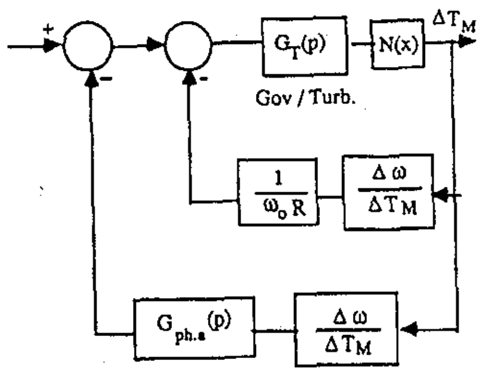

Fig.(4): Block diagram representation used for SCG ph-A design.

ii- For SCG, the block diagram shown in Fig. (2) is rearranged as shown in Fig.(4). From polar plot of $\Delta W/\Delta T_M$, the resonance frequency and the phase required are calculated. So, the phase advance network can be designed as:

$$G_{ph.a}(p) = K_{ph.a}\left((1+P\,T_{ph.a1}) / 1+P\,T_{ph.a2}\right) \qquad (12)$$

The recommended time constant ratio for SCG unit is 50. The cohice of the gain K_{ph-a} is very important to ensure the required stability specifications.

5. IMPLEMENTATION

Applying the design technique for different machines, then:

5.1 SCG Controller

Fig. (5.a) shows the polar plot of $\Delta w/\Delta T_M$. From this figure one can calculate: the phase advance circuit must provide around 74^0 at resonance frequency of 9.3 rad/s. So, $\alpha = 50$ and $T_{ph.a2}$ = 0.015 sec. Therefore the designed phase advance circuit has the following transfer function (including washout):

$$G_{ph.a}(P) = 0.008\ [PTw/(1+PT_w)][1+0.75P/1+0.015P] \qquad (13)$$

Tw = 1 : washout time constant.

5.2 Thermal Machine Controller

Figure (5.b) shows the polar plot of $\Delta W/\Delta E_f$ It may observed that, the PSS blocks should provide around 55^0 at 6.1 rad/sec. So, α + 10 and T = 0.052 sec. Therefore the thermal machine PSS has the following transfer function,

$$G_{PSS}(P) = 0.004\ [PT_w/(1+PT_w)][1+0.52P/1+0.052P] \qquad (14)$$

5.3 Hydraulic Machine Controller

Figure (5.c) shows the polar plot of $\Delta W/\Delta E_f$. It may noticed that, the PSS blocks must provide about 80^0 at 8.5 rad./sec. So, two cascade circuits must used (For conventional machines controllers, the phase angle obtained with each network must less than 60^0 otherwise the network becomes sensitive to measure noise). Hence, for each circuit $\phi_m = 40^0$ and $\omega_{max} = 8.5$ rad/sec. yields that α = 4.6 & T = 0.055 sec.. Therefore, the hydraulic machien PSS has the following transfer function:

$$G_{PSS}(P) = 0.005\ [PT_w/(1+PT_w)][1+0.25P/1+0.055P]^2 \qquad (15)$$

6. STABILITY ANALYSIS

The describing function analysis has been used to investigate the system stability and to study the possibilities of system failure. Replacing the nonlinear element by its describing function N(x) (Figs. 3 and 4), the overall transfer function becomes:

$$= G_{tot}(j\omega) \,.\, N(x) \,/\, (1+G_{tot}(j\omega) \,.\, N(x)) \qquad (16)$$

where, G_{tot} ($j\omega$) is the total transfer function ($P = j\omega$). If the characteristic equation is satisfied the system output exhibit a limit cycle. System stability is investigated by observing the position of G_{tot} ($j\omega$) relative to the locus of $-1/N(x)$. Figure (6) shows that all machines, with the designed controller, are stable with a gain and phase margins of a range which guarantee a satisfactory transient response. Also, it might be observed that the possibilities of system failure is denied as no limit cycle occurance.

7. CONCLUSIONS

The paper introduced an approach for modelling multimachine power system incuding a superconducting generator in frequency domain, which enable a great number of machines to be represented in details. With the aid of matrix elimination technique an equivalent model of any unit in the system were obtained and used as a base for controller design.

The paper also developed and applied a more simpler technique to design an appropriate controller for a SCG operating in a multi-machine environment. This is a multi-stage phase advance which improves the system stability and ensure satisfactory transient response. The stability limits were examined using the describing function analysis method. The results shows that all machines, with the designed controller, are stable with a suitable limits.

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9. NOMENCLATURE

H inertia constant (kWs/kVA)
I current (p.u.)
P differential operator
R resistance (p.u.)
T torque
V voltage (p.u.)
X reactance (p.u.)

Greek letters
δ rotor angle
ψ flux linkage (p.u.)
ω angular speed (rad/s)
Subscripts
a armature
d.q d and q components of stator winding
e.M electrical mechanical
f field
0 steady state
fKD_1,fKQ_1 d and q mutual components between outer screen and field winding SCG
fKD_2,fKQ_2 d and q mutual components between inner screen and field winding SCG
KD_1,KQ_1 d and q components of outer screen
KD_2,KQ_2 d and q components of inner screen
KD,KQ d and q damper winding for conv. M/CS.

APPENDIX-A

(i) Generator

SCG parameters
$X_d = X_q = 0.0453$ p.u. , $X_f = 0.541$ p.u.
$X_{KD1} = X_{KQ1} = 0.2567$ p.u. , $X_{FKD2} = 0.3398$ p.u.
$X_{af} = X_{fKD1} = X_{ad1} = X_{ad2} = X_{KD1\,KD2} = 0.237$ p.u.
$X_{aq1} = X_{aq2} = X_{KQ1\,KQ2} = 0.237$ p.u.
$R_{KD1} = R_{KQ1} = 0.01008$ p.u.
$R_a = 0.003$, RKD2 = RKQ2 = 0.00134 ,
H =3KWS/KVA

Data	Parameters for synchronous machines based on 500 MVA	
	Thermal	Hydro
MVA rated	552.MVA	231.6 MVA
KV rated	24 KV	13.8 KV
X_d	1.712	2.1077
X_q	1.702	1.59
X_f	1.652	1.733
X_{KD}	1.524	1.61
X_{KQ}	1.458	1.135
R_a	0.004	0.0045
R_f	0.00136	0.00069
R_{KD}	0.0118	0.0329
R_{KQ}	0.0171	0.0928
H	6.02	3.572
K_d	0.007	0.003
X_{ad}	1.467	1.5327
X_{aq}	1.457	1.0157

(ii) Exciter & AVR

Data	Parameters for synchronous machines based on 500 MVA	
	Thermal	Hydro
K_A	100	150
T_A	0.05	0.05
T_E	---	0.405
K_E	---	0.08
S_E	---	0.2
K_f	---	0.0648
T_f	---	1.0

APPENDIX-B

1. The excitation system transfer function is:
for thermal machine:

$$G_E = K_A / 1 + pT_A$$

for hydraulic machine:

$$G_E = K_A\,(1+pT_f)\,/\,(K_A(pK_f)+T_A AA_1 + AA_2)$$

where,

$$AA_1 = p^3\,T_f T_E + P^3\,(T_E+T_f(S_E+K_E))+P(S_E+K_E)$$
$$AA_2 = p^3\,T_f T_E + P\,T_E\,(T_E+K_E\,(1+PT_f))$$

2. The turbine and the governor transfer function for thermal machine:

for thermal machine:

$$\Delta T_M/\,\Delta\omega = -1\,/\,\omega_o R(1+PT_g)(1+PT_t) = G_t$$

while for hydraulic machine:

$$\Delta T_M/\Delta\omega = a_1p^2+a_2p+a_3\,/\,b_1\,p^4 + b_2\,p^3 + b_4\,p + b_5 = G_t$$

where:

$a_1 = T_r\,T_w$, $a_2 = -(T_r + T_w)$, $a_3 = -1$

$b_1 = 0.5\,\omega_o\,T_g\,T_p\,T_r\,T_w$

$b_2 = w_o\,[0.5\,T_w\,T_g\,(T_r + T_p) + T_g\,T_p\,T_r]$

$b_3 = w_o\,[T_r + T_p + 0.5\,T_w) + 0.5\,T_r\,T_w\,(\mu + \sigma)]$

$b_4 = w_o\,[\mu\,T_r+T_g + \sigma\,(0.5\,T_w + T_r)]$

$b_5 = w_o\,\sigma$

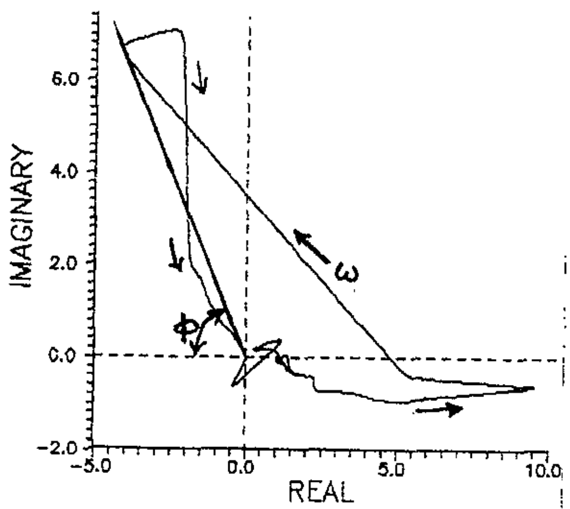
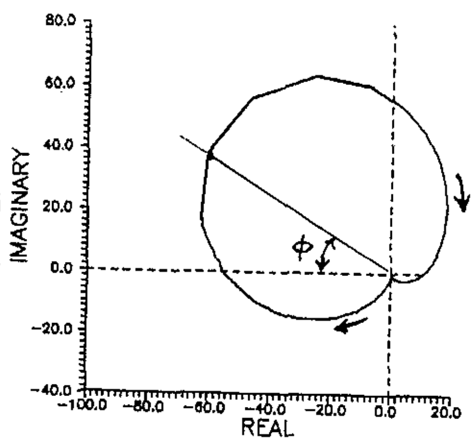


Fig.(5-a) . polar plot of $\Delta w\,/\Delta T_M$.



Figure(5.b) polar plot of $\Delta W\,/\,\Delta E_f$For thermal machine

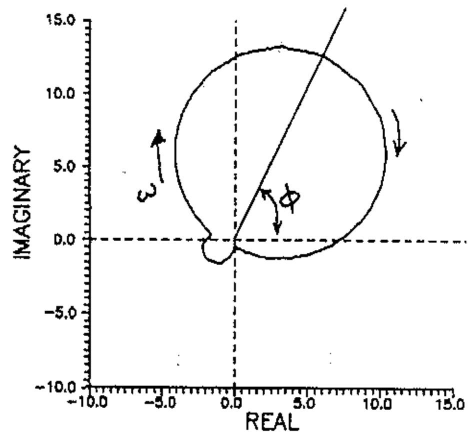


Figure (5.c) polar plot of ΔW / ΔE_f for hydraulic mach-

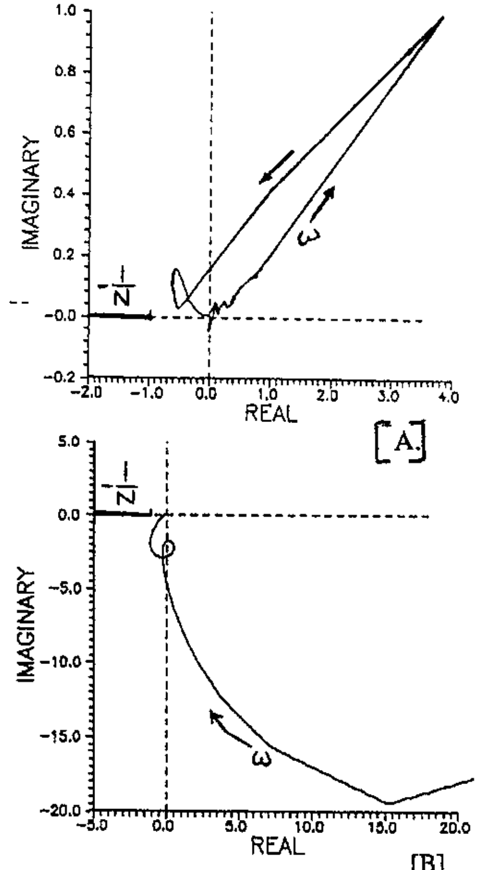


Figure (6) stability analysis

A– SCG **B– thermal machine**

" التحكم ودراسة الاتزان لالة فائقة التوصيل فى نظام قوى كهربية متعدد الالات "

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نظرا لزيادة الطلب على إستهلاك الطاقة الكهربية فى الاغراض التكنولوجيه المختلفة وبالتالى الاتجاه الى بناء وحدات توليد كبيرة وذات مقننات كبيرة إلا أن بارامترات تلك الوحدات تؤثر بالسلب على إتزان النظام ٠

يبدو الحل الامثل فى إستخدام الالات فائقة التوصيل والتى تتميز الى جانب صغر حجمها وكفاءتها العاليه بإمكانية التوليد عند جهد الشبكة مباشرة٠

ولكن من عيوب تلك الاله صعوبة التحكم فيها لأن الثابت الزمنى لدائرة المجال كبيرة (حوالى ١٥ دقيقه) وبالتالى فإن تحسين أداء هذه الاله يتم بالتحكم فى منظم البخار (الدخل الميكانيكى) ٠

هذا البحث يقدم طريقة مبسطه للتحكم فى آلة فائقة تعمل فى نظام قوى متعدد الالات ، وقد تم إيجاد نموذج مكافئ للآله فى النطاق الترددى (يأخذ فى الاعتبار التأثير المتبادل بين الوحدات المختلفة فى نظام القوى) ، ومن ثم إستخدام هذا النموذج كأساس لتصميم الحاكم٠

تم تصميم حاكمات للآلات التقليدية فى دائرة التغذية الكهربية (المجال) بينما تم تصميم حاكم للآلة فائقة التوصيل فى دائرة (منظم البخار) التغذية الميكانيكية٠

أخيرا تم دراسة إتزان النظام فى وجود الحاكمات وتبين أن إدخال الآلة فائقة التوصيل فى نظام القوى متعدد الآلات يتم بنجاح فى وجود الحاكم المصمم لها ، وأن النظام متزن فى مدى واسع من حدود الاتزان وأن إحتمالات حدوث إهتزازات مستمرة (ومايتبعها من إحتمالات إنهيار النظام) منعدمه فى وجود الحاكم المصمم٠