A New Approach for Investigation of the Turbine Generator Oscillatory Behavior Affecting Power System Quality and Reliability

Rajiv Kumar, Michael Merkle, Thomas Leibfried

Abstract—. **Transients following switching in the network and/or the tripping of generating unit auxiliaries can excite oscillatory torques on the turbine-generator-rotor-shaft system. The oscillations can be damped or amplified with time. Damped oscillations affect the power quality and if the oscillations grow with time they may even lead to generating unit outages (and damages) resulting in possible system instabilities. Deregulation of electricity markets has resulted in separation of Utility Companies (responsible for power generation) and Transmission Companies (responsible for power transmission). The decision making is no more under the same umbrella. Companies on both the sides have severe cost reduction focus and each side is tempted to make independent decision favourable to it. The Transmission Companies want to enhance transmission capacity of existing systems by introducing measures like series capacitor compensation. However incorporation of series capacitor compensation may under certain conditions lead to oscillations and also subsynchronous resonance. Currently, there is an urgent need to establish a systematic methodology to investigate the root cause of such oscillations so that preventive measures can be taken by both the Utility Companies and the Transmission Companies. This paper is a contribution in this direction. In this work,comprehensive dynamic model of synchronous generator system has been developed in software Matlab/Simulink. Generating unit start up and ramp loading to rated load has been simulated to get deeper insight into the oscillatory behaviour of the synchronous generator. Block loading of the turbine generator and sudden load shedding due to auxiliary trip have been investigated in detail. Further, power system network with bus connected parallel generating units and parallel transmission lines, having different series capacitor compensation ratio have been simulated in power system software NETOMAC. Transient conditions have been modelled to investigate the oscillations and the consequent torsional torques and angles between adjacent masses of the rotor shaft system causing fatigue life reduction. This work has very clearly revealed the complex dynamic interrelationship among variables responsible for power system oscillations..**

R. Kumar*, M. Merkle, T. Leibfried are with Institute of Electric Energy Systems and High-Voltage Technology (IEH), University of Karlsruhe (TH),
Kaiserstr. 12, 76128 Karlsruhe, Germany (Telephone : +49 / 721 / 608-6125, fax. : +49 / 721 / 69 52 24,
e-mail: kumar@ieh.uni-karlsruhe.de (*))

Index Terms-- **Turbine generator oscillations, synchronous generator model, torsional angle between rotors, bus connected parallel generating units, fatigue life of rotor, series capacitor compensation, Subsynchronous Resonance (SSR), time domain simulation, transmitted torque.**

I. INTRODUCTION

TURBINE generator oscillations may result due to several disturbances within the generating unit or in the power systems network. The important events that need to be investigated within the generating unit are synchronization and block loading, sudden load shedding due to say tripping of an important auxiliary like induced draft/ forced draft fan and opening of HP/LP bypass system. On the power system network side, short circuit faults particularly when the transmission lines are series capacitor compensated, may lead to serious oscillations. So far the power industry attitude has been to feel content if such oscillations are damped and the generator remains synchronized to the grid. In the post liberalized electricity market scenario (i) there are much more stringent power quality and reliability requirements (ii) Utility Companies are not only keen to operate the units to their full designed life but also want a life extension of the existing turbine generators beyond the designed life, rather than accepting reduction of fatigue life due to oscillations. However independent decisions made by Transmission Companies like providing economically attractive series capacitor compensation of AC transmission systems (to increase maximum power carrying capacity of existing transmission lines,) may increase the possibility of causing the generating unit oscillations and even the subsynchronous resonance. Better understanding of the dynamics and root cause of oscillations is thus extremely important in the current power system scenario. In this paper, oscillation dynamics has been investigated first separately for the synchronous generator as a function of variations in the turbine mechanical torque input simulated in Matlab/Simulink. In the second step, power system network with bus connected parallel generating units connected to series capacitor compensated transmission has been modeled in software NETOMAC. The dynamic behavior has been investigated following three phase short circuit fault on the electrical network. The new approach of using the results of two softwares namely Matlab/Simulink and NETOMAC in a complementary manner as demonstrated in this paper can be very useful for both Utility and the Transmission Companies for power system related decision making.

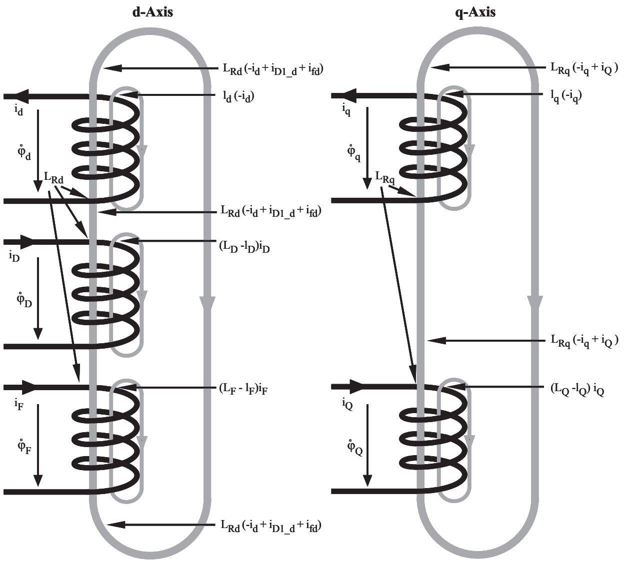


Fig. 1. Flux linkages for d-Axis and q-Axis

II. METHODOLOGY

The differential equations of the synchronous generator model are developed first in the integral form and then transformed into *s*- space. These equations are further resolved with additional variables to get following equations (1) to (19). Nomenclature used is given in Table 1. Solid iron rotor used in large steam turbine generators providing multiple paths for circulating eddy currents that act as equivalent damper windings (one damper winding in d-axis and one damper winding in q-axis) has been considered. The flux linkages for d-Axis windings and q-Axis windings are shown in Fig. 1. The voltage and current equivalent circuits for one machine infinite bus system, d-Axis and, q-Axis are shown in Fig. 2. Equations (1), (2) and (3) give the flux linkages in the d-Axis component of stator winding, field excitation winding, and d-Axis damper winding respectively as illustrated in Fig.1 left side. Similarly Equations (8) and (9) give the flux linkages in

Table 1 - Nomenclature

Quantity	Symbol	*Quantity*	Symbol
Voltage	u	d-Axis Stator quantities	$u_d, i_d, \varphi_d, L_d, l_d, r_R$
Current	i	q-Axis Stator quantities	$u_q, i_q, \varphi_q, L_q, l_q, r_R$
Flux linkage	φ	Rotor excitation quantities	$u_F, i_F, \varphi_F, L_F, l_F, r_F$
Power	p	d-Axis damper quantities	$u_D, i_D, \varphi_D, L_D, l_D, r_D$
Resistance	r	q-Axis damper quantities	$u_Q, i_Q, \varphi_Q, L_Q, l_Q, r_Q$
Inductance	L	d-Axis air gap quantities	φ_{AD}, L_{Rd}
Leakage inductance	l	q-Axis air gap quantities	φ_{AQ}, L_{Rq}
Time	t	Generator terminal quantities	u_R, i_R, R
Angular velocity	ω	d-Axis Generator terminal	u_d, i_{td}
Angle	$\theta or \delta$	q-Axis Generator terminal	u_q, i_{tq}
Inertia constant	H	Transmission line quantities	i_{tR}, L_e, R_e
Laplace operatror	s	Infinite bus quantities	U_∞, L_e, R_e
Time scaling factor	a	Mech.,Elect.,Daming Torque	T_m, T_e, D

the q-Axis component of stator winding, and q-Axis damper winding respectively as illustrated in Fig.1. Equations (6), (7) and (12) give the currents in the d-Axis component of stator

$$\varphi_d = \frac{\omega_B}{a.s}\{\frac{r_R}{l_d}(\varphi_{AD}-\varphi_d)-\omega\varphi_q-u_d\} \quad (1)$$

$$\varphi_F = \frac{\omega_B}{a.s}\{\frac{r_F}{l_F}(\varphi_{AD}-\varphi_F)+u_F\} \quad (2)$$

$$\varphi_D = \frac{\omega_B}{a.s}\{\frac{r_D}{l_D}(\varphi_{AD}-\varphi_D)\} \quad (3)$$

$$\frac{1}{L_{MD}} = (\frac{1}{L_{Rd}}+\frac{1}{l_d}+\frac{1}{l_F}+\frac{1}{l_D}) \quad (4)$$

$$\varphi_{AD} = L_{MD}(\frac{\varphi_d}{l_d}+\frac{\varphi_F}{l_F}+\frac{\varphi_D}{l_D}) \quad (5)$$

$$i_d = \frac{1}{l_d}(\varphi_d-\varphi_{AD}) \quad (6)$$

$$i_F = \frac{1}{l_F}(\varphi_F-\varphi_{AD}) \quad (7)$$

$$\varphi_q = \frac{\omega_B}{a.s}\{\frac{r_R}{l_q}(\varphi_{AQ}-\varphi_q)+\omega\varphi_d-u_q\} \quad (8)$$

$$\varphi_Q = \frac{\omega_B}{a.s}\{\frac{r_Q}{l_Q}(\varphi_{AQ}-\varphi_Q)\} \quad (9)$$

$$\frac{1}{L_{MQ}} = \frac{1}{L_{Rq}}+\frac{1}{l_q}+\frac{1}{l_Q} \quad (10)$$

$$\varphi_{AQ} = L_{MQ}(\frac{\varphi_q}{l_q}+\frac{\varphi_Q}{l_Q}) \quad (11)$$

$$i_q = \frac{1}{l_q}(\varphi_q-\varphi_{AQ}) \quad (12)$$

$$i_{td} = \frac{\omega_B}{aL_e.s}\{\sqrt{3}U_\infty sin\delta+u_d-R_ei_d-\omega L_ei_q\} \quad (13)$$

$$i_{tq} = \frac{\omega_B}{aL_e.s}\{-\sqrt{3}U_\infty cos\delta+u_q-R_ei_q+\omega L_ei_d\} \quad (14)$$

$$u_R = (i_R-i_{tR})R \quad (15)$$

$$u_d = (i_d-i_{td})R \quad (16)$$

$$u_q = (i_q-i_{tq})R \quad (17)$$

$$\omega_{\triangle u} = \frac{1}{2Ha.s}\{T_m-T_e-D\omega_{\triangle u}\} \quad (18)$$

$$\delta = \frac{\omega_B}{a.s}\{\omega_\triangle\} \quad (19)$$

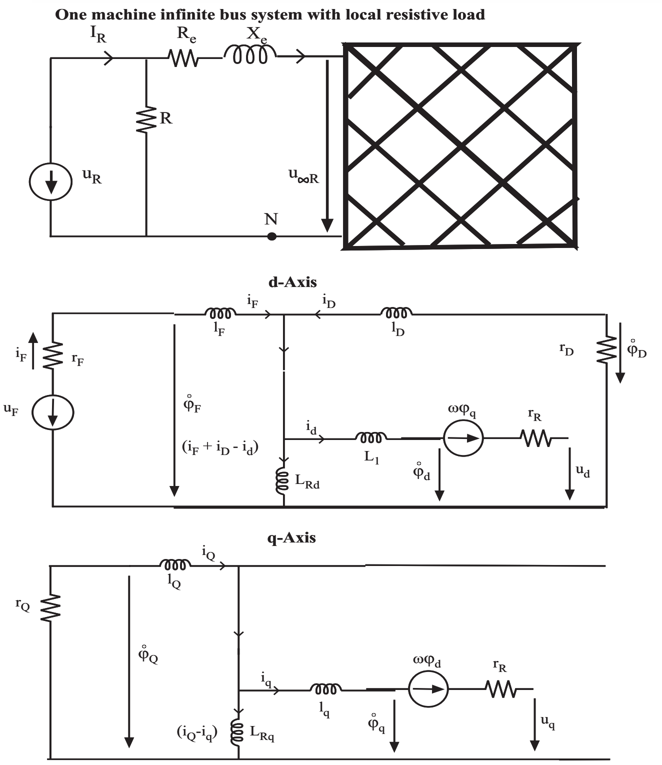


Fig. 2. Equivalent circuits for (1) one machine infinite bus system, (2) d-Axis and (3) q-Axis

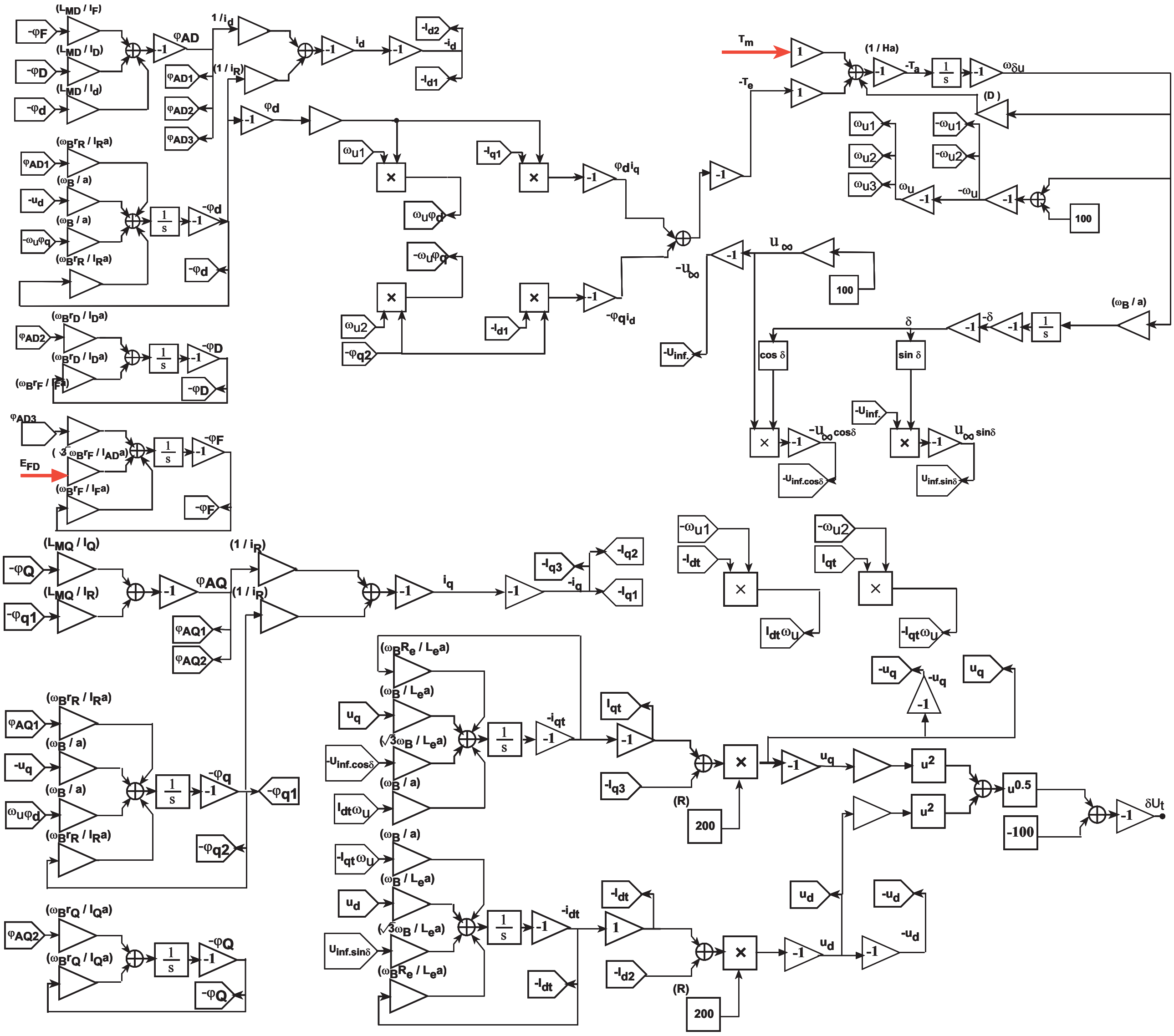


Fig. 3. Simulink model for synchronous generator connected to infinite bus.

winding, field excitation winding and q-Axis component of stator winding as illustrated in Fig.2. Similarly Equations (15), (16) and (18) give the generator stator terminal voltage of phase R, d-Axis component, and q-Axis component of terminal voltage respectively as illustrated in Fig.2. Equations (13), and (14) give the d-Axis component, and q-Axis component of current flowing in the transmission line. Equation (18) gives the variation in angular velocity of generator rotor and equation (19) gives the load angle. The detailed basis for developing these equations can be found in references [6], [9], and [11]. Based on equations (1) to (19) we have developed the Simulink model for synchronous generator connected to infinite bus for investigations as shown in Fig.3.

The dynamic behavior of the synchronous generator has been investigated during block loading (10% step load), ramp loading to rated load and sudden load shedding. For investigating the dynamic behavior of the total system the power system network with bus connected parallel generating units and parallel transmission lines with different series compensation ratios have been simulated in power system software NETOMAC. The turbine generator parameters considered are the same as given in IEEE First Benchmark [3]. The system frequency is 60 Hz.

Complex dynamic relationship among oscillations of electrical torque, mechanical torque, transmitted torques, and angle deviation between adjacent rotor sections have been investigated.

III. CASE STUDIES

A *Generator Block Loading, Ramp Loading to Rated Load, and Steady State Operation*

Generator block loading to 10% of the rated torque and ramp loading to rated torque has been simulated in Matlab/Simulink. Input mechanical torque and output electrical torque characteristics of the synchronous generator during (1) block loading, (2) ramp loading to rated torque and (3) steady state operation is shown in Fig.4. Time function of d-Axis and q-Axis components of stator (1) current (2) voltage and (3) flux linkage during block loading, ramp loading to rated torque and, steady state operation corresponding to Fig.4 are shown in Fig.5. This is a case of hot startup and the generator is run up to rated torque through mechanical steam torque input in about 50 minutes time from synchronization to achieving full load. At time point marked T_1 in Fig. 4, the generator system is block loaded to 10% of the rated torque by applying 10% mechanical torque step input. At time point T_2 ramp loading of the generator begins through mechanical torque ramp input and rated torque is achieved at time point T_3. The generator is running at rated torque steady state conditions at time point T_4. At all these important time points the oscillatory behavior of the generator system has been critically examined.

During ramp loading to rated torque there are no oscillations. The most interesting cases are the generator block loading and sudden load shedding which have been investigated in detail in the following sections.

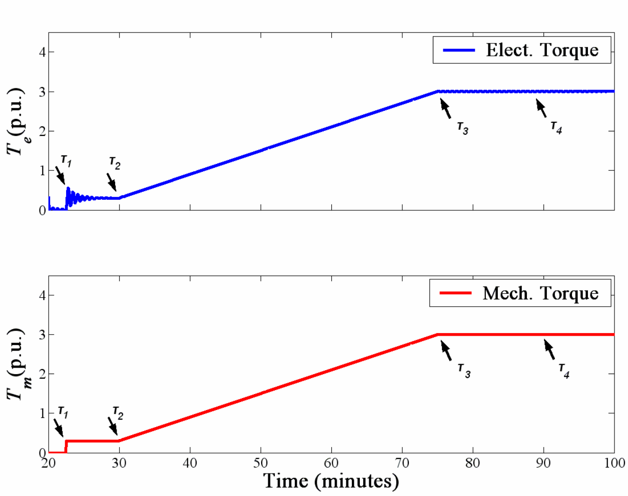


Fig. 4. Input mechanical torque and output electrical torque of the synchronous generator during (1) block loading, (2) ramp loading to rated torque and (3) steady state operation .

B Investigation of Generator Block Loading to 10% of the Rated Torque

Generator synchronization and block loading are the normal operating conditions for a generating unit. In fact, in the two shift operation the units are started and stopped everyday. Hence the block loading condition at time point T_1 in our model has been investigated to understand the complex dynamic relationship among electrical torque generated by the synchronous generator and state variables namely speed of the rotor, load angle, d-Axis and q-Axis flux linkages and the d-Axis and q-Axis currents and voltages. The time function of generator (1) rotor speed (2) load angle and (3) electrical torque and (4) mechanical torque input consequent upon 10% block loading is shown in Fig. 6. It can be clearly observed that very small oscillations (of maximum amplitude less than 0.02 rpm) following the application of 10% mechanical step torque

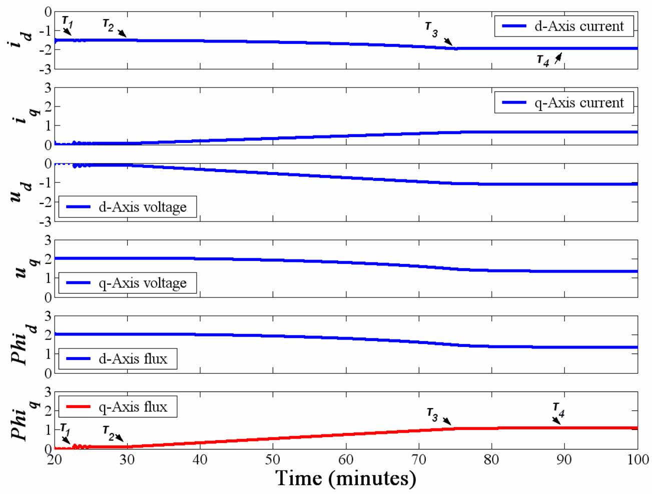


Fig. 5. Time function of d-Axis and q-Axis components of stator (1) current (2) voltage and (3) flux linkage during block loading, ramp loading to rated torque and, steady state operation corresponding to Fig.4

input result in damped oscillations of maximum amplitude about 0.2 p.u.(i.e. about 60% of the step input mechanical torque to the generator). Speed oscillations result in load angle oscillations as can be seen in the Fig. 6.

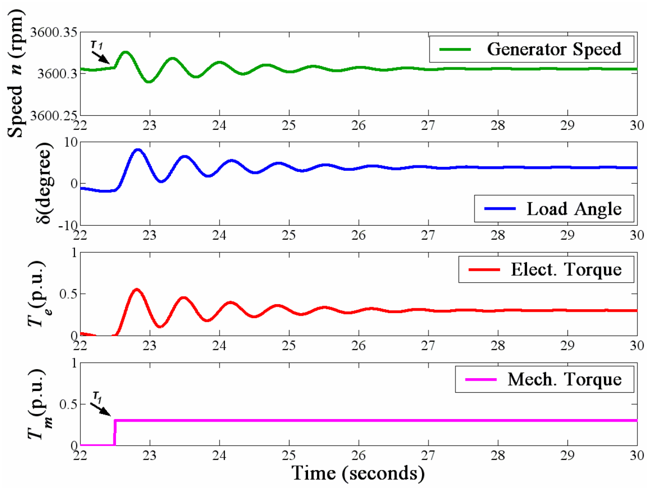


Fig. 6. Time function of generator (1) rotor speed (2) load angle and (3) electrical torque and(4) mechanical torque input consequent upon 10% block loading of generator

Simulation results have shown that d-Axis components of stator flux i.e φ_d and the and q-Axis current i_q, show no significant oscillations following block loading. On the contrary, q-Axis components of stator flux φ_q and the d-Axis currents i_d have significant oscillations following block loading as shown in Fig. 7. This is because even a small change in speed when multiplied with large flux linkage in the d-Axis i.e φ_d (as excitation is applied in the d-Axis) results in a significant change in the speed voltage term $\omega\varphi_d$ in the q-axis. Hence the q-Axis flux linkage which depends on the product $\omega\varphi_d$ follows the oscillations of speed, i.e. ω. Since the absolute value of q-Axis flux linkage φ_q, is much smaller as compared to the d-Axis flux linkage φ_d (because there is no excitation input in the q-Axis) the speed voltage term in d-Axis, i.e. $\omega\varphi_q$

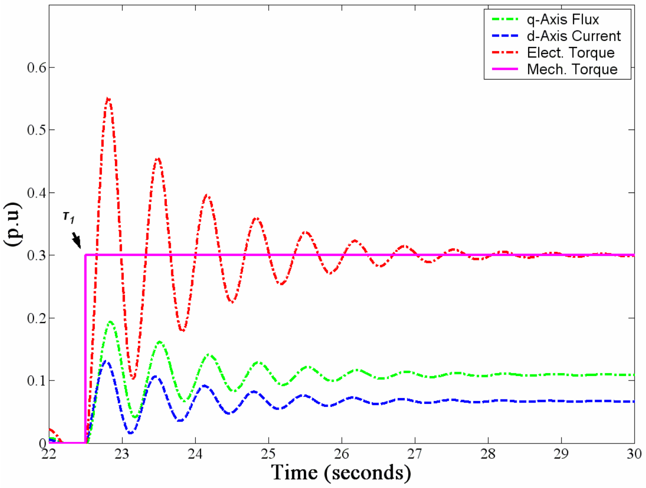


Fig. 7. Time function of generator stator winding (1) q-Axis flux linkage (2) d-Axis current and (3) electrical torque and (4) mechanical torque consequent upon 10% block loading of generator

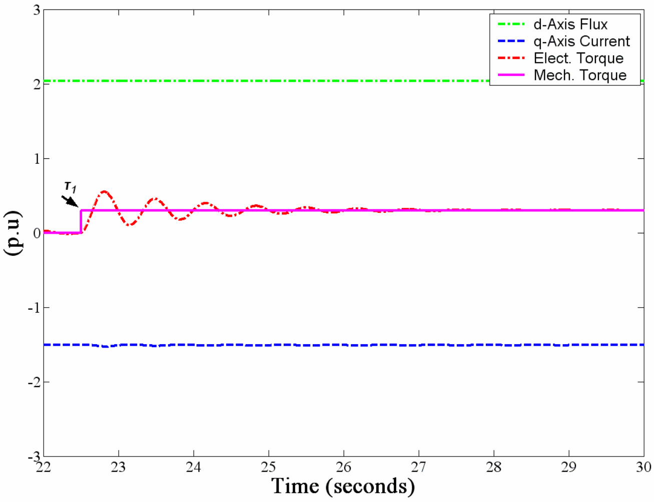


Fig. 8. Time function of generator stator winding (1) d-Axis flux linkage (2) q-Axis current and (3) electrical torque and (4) mechanical torque consequent upon 10% block loading of generator

is very small and no significant oscillations are observed in d-Axis flux linkage φ_d , even though there are small oscillations in the term $\omega\varphi_q$ itself. However, these small oscillations in term $\omega\varphi_q$ are large enough to cause an oscillating difference between the instantaneous values of flux linkage φ_d and φ_{AD} (as refered to Fig. 3). Also the oscillations in load angle δ lead to oscillation in the d-Axis component of the voltage u_d due to the fact that the term $U_\infty \sin\delta$ varies significantly to the result of even small variations in δ. These oscillations in u_d also contribute to the oscillations in the difference term (φ_d - φ_{AD}) which leads to the oscillations in d-Axis current as can be observed in Fig. 7. It has been observed that there are no significant oscillations in the q-Axis current i_q,as the variations in the terms φ_d and u_q are insignificant as there is no excitation in q-Axis and the term $U_\infty \cos\delta$ does not vary much for small variations of load angle δ. Hence, the difference term (φ_q - φ_{AQ}) does not show significant variations, which is why, no oscillations are observed in i_q as can be seen in Fig. 8. In the electrical torque equation "$T_e = i_q \varphi_d - i_d \varphi_q$" , the first term (i.e. $i_q \varphi_d$) varies due to oscillating i_q. Since φ_d is large, the product term $i_q \varphi_d$ shows significant oscillations. Similarly the second term i.e. $i_d \varphi_q$ varies due to oscillations in i_d. Moreover, since the sign of i_d is negative, the oscillations in second term add to that of the first term resulting in significant oscillations in torque T_e following block loading as seen in Fig. 6. Also it is observed that, the damped oscillations have a very low frequency of less that 0.7Hz as seen in Fig. 6. This frequency is much below the lowest natural frequency of the turbine generator rotor shaft system. Hence there is no possibility of subsynchronous interactions between the electrical torque and the mechanical torque delivered to generator by the turbine rotor shaft system.

C Investigation of Generator Sudden Load Shedding

Generator sudden load shedding can occur due to events like tripping of one of the 2*60% induced or forced draft fans or tripping of one of the running boiler feed pumps when the standby pump is not available or due to opening of HP/LP bypass system. Load of about 40% of the rated load has to be shed suddenly in such events to save the generating unit from tripping. We have simulated such an event of 40% load shedding by step reduction of 40% in the rated mechanical torque input when the generator is running in steady state condition at rated torque. This refers to time instant T_5 shown in Fig. 9 to investigate the torque oscillations. The Time function of generator (1) rotor speed (2) load angle and (3) electrical torque and (4) mechanical torque consequent upon 40% load shedding off the generator is shown in Fig. 9. It can be clearly observed that speed oscillations (of maximum amplitude less than 0.1 rpm) following sudden load shedding result in damped oscillations of maximum amplitude about 0.9 p.u.(i.e. about 50% of the value of load shedding i.e 1.8 p u in input mechanical torque) Such oscillation amplitudes are very

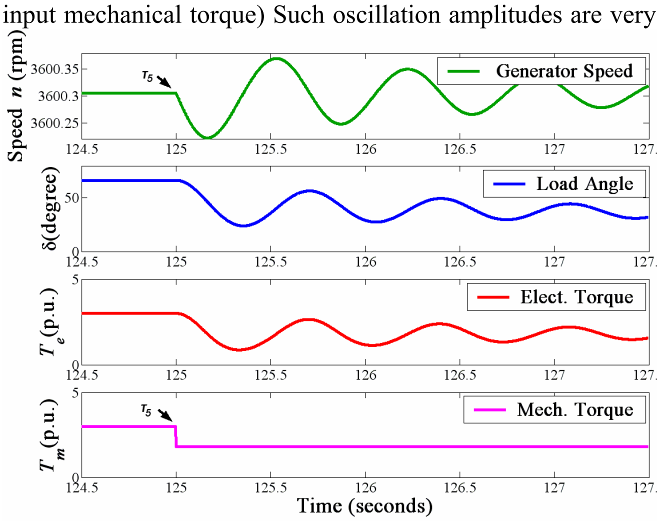


Fig. 9. Time function of generator (1) rotor speed (2) load angle and (3) electrical torque and (4) mechanical torque consequent upon 40% load shedding off generator

significant and affect the power quality till the time they are damped out. The speed oscillations result in load angle oscillations as can be seen in the Fig. 9. The oscillations observed in q-Axis components of stator flux φ_q and the d-

Axis current following the sudden load shedding are shown in Fig. 10. This case study provides an interesting insight into the physical behavior of the machine in the event of a transient condition e.g. sudden load shedding in this case. On the occurrence of a transient the balance between the generator electrical torque output and the mechanical torque input to generator from turbine gets disturbed. This leads to a small acceleration or deceleration of rotor depending upon whether the steam input to the turbine is increased or reduced. This results in change in relative rotor position with respect to the reference. In the case of a sudden load shedding (i.e. the step reduction of steam input to turbine) the rotor slows down and hence the load angle (i.e. angle of rotor q-Axis or generator induced voltage w.r.t. infinite bus voltage reference) decreases. Thus the power transmitted and the electrical torque output decrease to a value lower than the new value of mechanical torque input due to the rotor inertia. When the electrical toque output goes lower than the new value of mechanical torque input, the rotor starts accelerating. However it is important to note that the load angle and hence the electrical torque output continue to decrease even after rotor begins to accelerate from its minimum value till the rotor speed reaches the rated speed as can be seen in Fig. 9. Due to inertia, the rotor continues to accelerate beyond the rated speed and only when the rotor speed increases above the rated speed the load angle starts increasing resulting in the increasing electrical torque. This process of acceleration and deceleration of rotor continues leading to power oscillations till they are damped out. It may be mentioned here that the power plant operators hardly notice this acceleration and deceleration of the rotor as the maximum speed change w.r.t. to rated speed is less than 0.1 rpm. However the operators do notice the consequent power oscillations which are very significant. It is observed that the damped oscillations have a very low frequency of less than 0.7Hz as seen in Fig. 10. This frequency is much below the lowest natural frequency of the turbine generator rotor shaft system. Hence in this case also there is no possibility of subsynchronous interactions between the electrical torque and the mechanical torque delivered to generator by the turbine rotor shaft system.

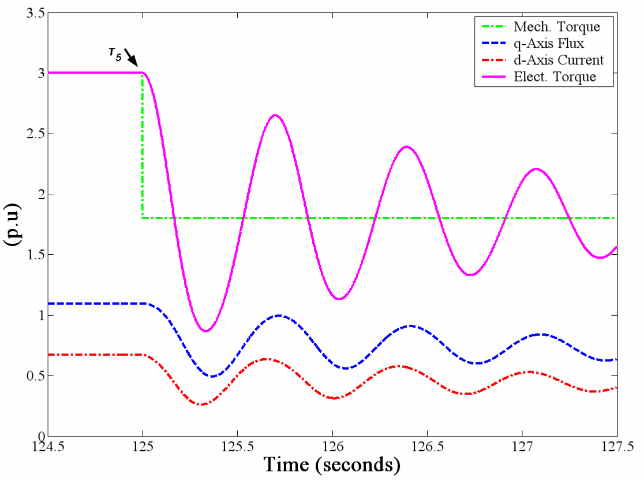


Fig. 10. Time function of generator stator winding (1) q-Axis flux linkage (2) d-Axis current (3) electrical torque and (3) mechanical torque input consequent upon 40% load shedding.

D. Investigation of Oscillatory Interactions between Power System Network and Turbine Generator Rotor Shaft System for Bus Connected parallel Generators with three parallel Lines (each having different series compensation ratio) Transmission System

IEEE First Benchmark [3], has been simulated in the power system software NETOMAC.

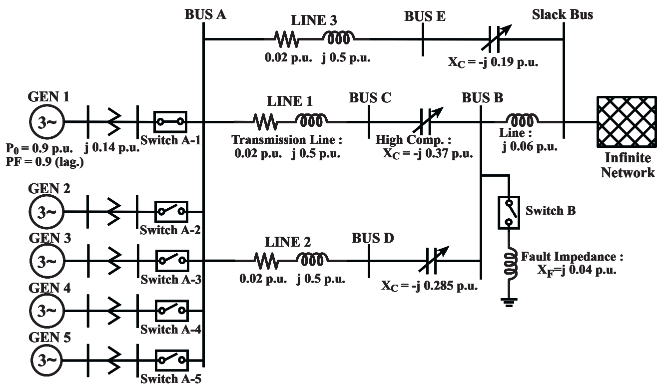


Fig. 11. Power system network for Subsynchronous Resonance (SSR) studies

The power system network is shown in Fig. 11 and the lumped spring mass model of the turbine generator rotor in Fig. 12. The system frequency is 60 Hz. For validating the model with IEEE First Benchmark [3], only (a) single generator namely "GEN 1" is connected to Bus A and (b) single transmission line namely "LINE 1" is connected

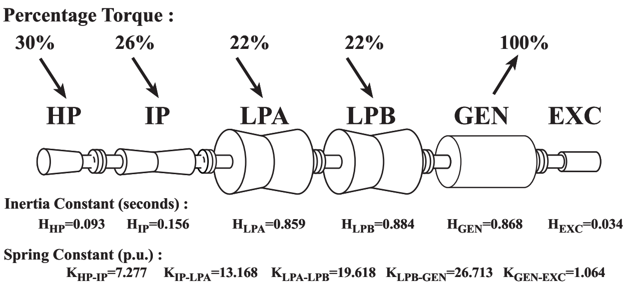
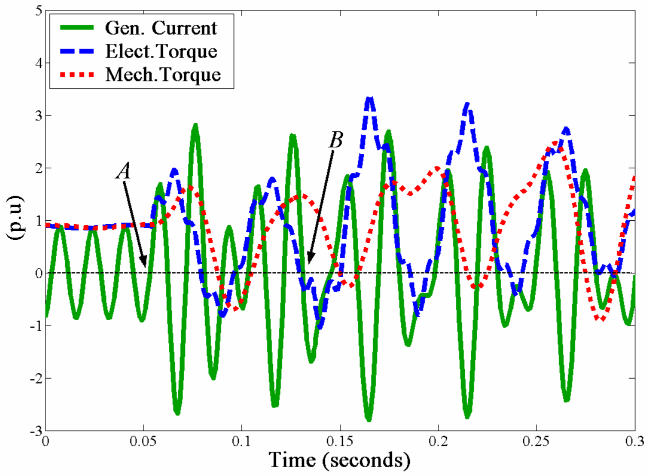


Fig.12 Rotor shaft system of turbine generator rotor.

between Bus A and Bus B. The time domain simulation is carried out by simulating a disturbance of 3-phase to ground short circuit at BUS B (as shown in Fig. 11.) at the time instant

marked by point ***A*** in Fig. 13 when the voltage on phase R of BUS B crosses zero. The disturbance is eliminated after 0.075 s at the time instant marked by point ***B*** in Fig. 13 phase by phase when phase current crosses zero. Transient time domain simulation results (with 74.2% series compensation ratio) indicating generator current, electrical torque and mechanical torque with time are shown in Fig. 13. We can clearly see the sequence of events leading to the SSR oscillations. The simulation results compare well with IEEE Benchmark [3], as reported in [2], by the authors hence establishing the validity of our model.

After establishing the validity of model with IEEE First Benchmark [3], time domain simulations have been carried out for (a) single generator, (b) two parallel generators, and (c) five parallel generators connected to three transmission lines each having different series compensation ratio. In all cases the time domain simulations have been done by simulating a three-phase short circuit fault at BUS B (as shown in Fig. 11.). The fault is cleared after 75 milliseconds. The worst case torque oscillations are experienced when two generating units are running in parallel. We have investigated the torque oscillations and the angular torsions for this worst



case and the

Fig. 13. Transient time domain simulation results with 74.2% series compensation ratio (generator current, electrical torque and mechanical torque characteristics as a function of time).

results are shown in Fig. 14 and Fig. 15. This is a typical case of SSR and it can be seen that the amplitudes for torsional torques and the resulting angular torsions between the rotor shaft sections is very high and also the oscillations are growing with time. Such transients have the potential to damage the rotor, particularly if they become unstable causing generating unit outage affecting the power system reliability.

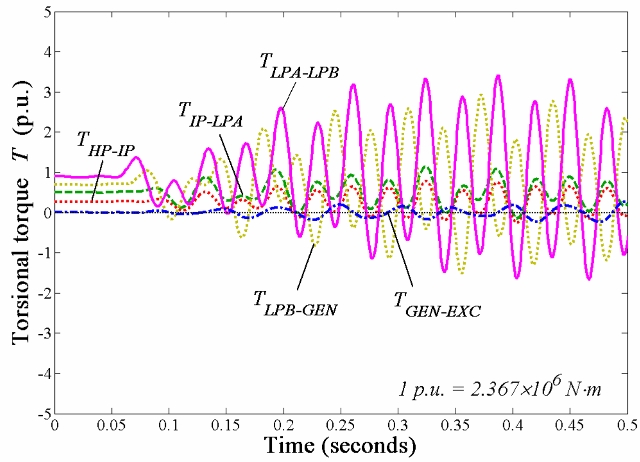


Fig. 14. Transmitted torques between rotor shaft sections for bus connected two parallel generators with three parallel lines..

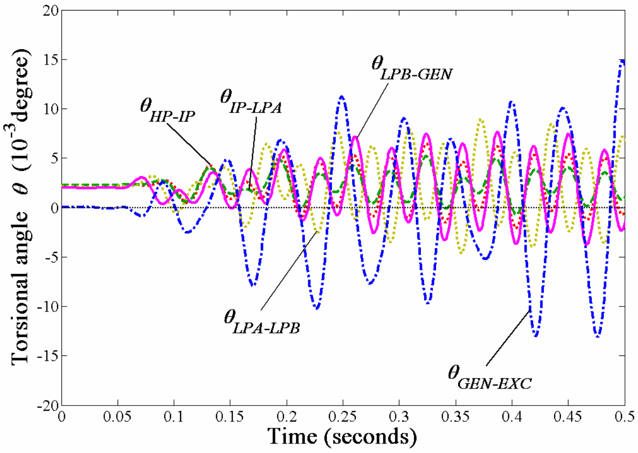


Fig. 15. Angle difference between adjacent rotor masses for bus connected two parallel generators with three parallel lines.

E. Complementary use of Simulation Software Matlab/Simulink and NETOMAC

Software Matlab/Simulink have been used to model Generator and turbine to simulate turbine generator block loading, ramp loading to rated load and load shedding which is very close to real life situation in an operating plant. Such simulation is difficult with NETOMAC. Moreover with Matlab/Simulink models we have been able to investigate the dynamic behavior of each and every variable including flux linkage, voltage, and currents of d-Axis and q-Axis windings, rotor speed, load angle and electrical torque to establish the root cause of oscillations. NETOMAC being a closed program does not provide such an opportunity as we cannot observe the behavior of all the d-Axis and q-Axis variables even though these variables are internally calculated. On the other hand modeling complex power system with a number of transmission lines having different series compensation ratio and bus connected parallel generators is much easier in NETOMAC and difficult in Matlab/Simulink. Hence such a complex power system has been modeled by us in NETOMAC. Further since NETOMAC does not give the torsional angles between the adjacent turbine generator masses, we have exported the torsional torques (following three-phase short circuit fault) computed in NETOMAC to Matlab to determine the torsional angles affecting the fatigue life. Thus in this complementary approach we have (i) understood the complex dynamic behavior and interrelations of different variables to establish the root cause through detailed and visible models of Matlab/Simulink (ii) modeled the complex power system in NETOMAC and (iii) finally exported the results of NETOMAC to Matlab to carry out further computations to get a deeper insight into the dynamic behavior of the system.

IV. CONCLUSION

This paper has clearly demonstrated the methodology for carrying out dynamic simulation studies for investigating the turbine generator oscillatory behavior during (1) block loading of generator system to 10% of the rated torque (2) sudden load shedding off 40% of the rated torque when the generator is running at full load in steady state condition and (3) subsynchronous resonance condition caused by a disturbance of 3-phase to ground short circuit for a power system with bus connected parallel generators connected to three transmission lines each having different series capacitor compensation ratio. The first two case studies (simulated in Matlab/Simulink) i.e. generator block loading and generator sudden load throw off have clearly established the root cause dynamics of oscillatory behaviour of the generator electrical torque following a disturbance and the effects of same on power quality till such oscillations are damped out. The third case study (simulated in power system software NETOMAC) i.e. power system with series compensated transmission lines has revealed the severity of oscillation of transmitted torques between rotor shaft sections and the resulting torsional angle difference between adjacent rotor masses. The investigation approach demonstrates as to how different simulation softwares namely Matlab/Simulink and NETOMAC can be used in a complementary manner to get deeper insight into the dynamics of turbine generator oscillatory behavior affecting power system quality and reliability. This work can be very useful not only for the power system planning decisions but also for operating power stations.

V. References

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VI. Biographies

Rajiv Kumar was born in Junpat, India, in 1958. He received his B.Sc. (Electrical & Electronics) Engineering & Master of Business Administration (MBA), from the University of Delhi, India in 1979 and 1996 respectively and M.Sc. (Electrical Engineering) in 2003 from the Institute of Electric Energy Systems and High-Voltage Technology, University of Karlsruhe, Germany. From 1979 onwards he has been working in National Thermal Power Corporation (NTPC) of India in the engineering department for 17 years (on basic and detailed engineering of new projects, renovation & modernisation of old projects, consultancy projects), erection and commissioning of 432 MW combined cycle Faridabad Gas Power Station for two and a half years, Operation & Maintenance of National Capital Power Station - Dadri (840 MW Coal Fired and 817 MW Combined Cycle Power Plant) for two years as Deputy General Manager. Since December 2001 he is a researcher with the Institute of Electric Energy Systems and High –Voltage Technology, University of Karlsruhe, Germany working in the area of Electric Power System.

Michael Merkle was born in Freiburg, Germany, in 1971. He studied at Universities of Stuttgart, Karlsruhe, and Dublin and received his Dipl.-Ing.-degree in 1998. He received his PhD degree in 2002 from the in the Institute of Electric Energy Systems and High-Voltage Technology, University of Karlsruhe. His research interests are power system stability, load modelling and FACTS.and Sub-Synchronous Resonance.

Thomas Leibfried was born in Neckarsulm, Germany, in 1964. He studied Electrical Engineering at the University of Stuttgart and received his Dipl.-Ing. and Dr.-Ing. degree from the University of Stuttgart, Germany, in 1990 and 1996 respectively. He joined Siemens in 1996. After working in the field of transformer monitoring and basics in transformer design Dr. Leibfried changed in 1999 to the quality department as head of the test departments of the transformer factories Nuremberg and Dresden. Beginning from 2001 he worked as Technical Manager in the Service department, where he was responsible for the development of service activities world wide. At the end of 2002 Dr. Lebfried became head of the Institute of Electric Energy Systems in Karlsruhe, Germany, and Professor in the faculty of Electrical and Information Engineering. Prof. Leibfried is member of IEEE and VDE.