Design And Implementation Of Series Connected FACTS Devices For Enhancing Powersystem Oscillation Damping

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***Abstract*—This paper presents a way to increase power transfer capability of the system and improve power oscillation damping by series connected two FACTS devices, Thyristor Controlled Series Capacitor (TCSC) and a Thyristor Controlled Phase Angle Regulator (TCPAR). This paper also describes a practical implementation and analysis of proposed system in laboratory.**

Keywords- Power oscillation, TCSC,TCPAR.

I. INTRODUCTION

Low frequency oscillations which arise between areas in large inter connected power networks is a problem of current interest in power industry. These low frequency oscillations are related to small signal stability of power system and are detrimental to goal of maximum power transfer and power system stability[1-2]. In recent years, greater demands have been placed on transmission networks, as a result power systems began to operate closer to their stability limits [4]. Induction motors which are widely used in consumption units are major part of dynamic loads especially in large industries and air-conditioning in the commercial and residential areas.[3]The dynamic characteristics of the load affect the damping of the power systems. Power system stabilizers (PSSs) are extensively used in power industry to enhancethe damping of electric power systems and Automatic Voltage Regulators (AVRs) helped to improve the steady state stability of power system, but transient stability became a concern for the power system operators[5].

There was a greater need for fast responding alternative technology made of semiconductor devices to solve much of the problems in power transmission. The need was fulfilled with the invention of Thyristor switch (semiconductor device) opened the door for the development of power electronics device known as Flexible AC Transmission Systems (FACTS) controllers.The operational flexibility and controllability that FACTS has to offer will be one of the most important tools for the system operator in the changing utility environment[6-7].

This paper addresses the related subject of system performance improvement due to the coordinated control action of series connected FACTS devices such as TCSC and TCPAR.This prior work include three separate tasks: i) siting and system performance analysis of TCSC for increased power transfer and damping power oscillations; ii) system performance analysis of TCPAR for increased power transfer and damping power oscillations; iii) investigation of the potential additional performance benefits that can be realized by coordinated control of both TCSC and TCPAR.

II. SYSTEM MODEL

The system used for this study represents a scale down model of a generation plant that delivers power to an infinite bus through a transmission line[8]. A low frequency oscillation is created on the system by weakening the damping torque and applying a sudden change in the load. These small disturbance lead to a steady increase or decrease in generator rotor angle and leads to transient instability. System performance during above condition is analyzed under the following cases.

i) System model without FACTS devices.
ii) System model with TCSC.
iii) System model with TCPAR.
iv) System model with coordinate control of TCSC and TCPAR.

The proposed system consist of a synchronous generator connected to an infinite bus with two FACTS devices TCSC and TCPAR connected in series with the transmission line as shown in Fig. 1.

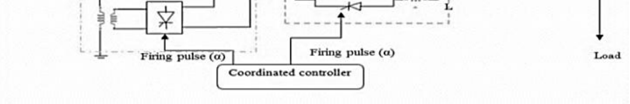


Fig1. System model

The synchronous generator is delivering power to infinite bus through series compensated transmission line. Series compensation is provided by TCSC and TCPAR.The generator terminal voltage is represented as $V_s$and infinite bus voltage is represented as $V_r\llcorner\delta$. The operating load angle is δ. The control of TCSC and TCPAR is done with a coordinate controller.

A. Modelling of Thyristor Controlled Series Capacitor(TCSC).

TCSC is one of the best known series FACTS controllers that have been in use for many years to increase line power transfer as well as to enhance system stability[9]. The basic module of TCSC is shown in Fig 2. It consist of three components : capacitor bank C , bypass inductor L and bidirectional thyristor $T_1$and T_2 .The firing angles of the thyristors are controlled to adjust the TCSC reactance in accordance with a system control algorithm.

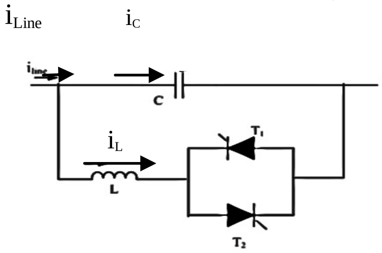


Fig 2. Basic module of a TCSC

According to the variation of the thyristor firing angle (α)or conduction angle (σ), this process can be modeled as a fast switch between corresponding reactance offered to the power system. Assuming that the total current passing through the TCSC is sinusoidal; the equivalent reactance at the fundamental frequency can be represented as a variable reactanceX_{TCSC}. There exists a steady-state relationship betweenα and the reactance X_{TCSC}. This relationship can be described by the following equation [12].

$$X_{TCSC}=\frac{X_c\times X_L(\alpha)}{X_L(\alpha)-X_c} \qquad (1)$$

$$X_L(\alpha)=\frac{X_L\times\pi}{\pi-2\alpha-\sin\alpha} \qquad (2)$$

$$X_L=2\pi fL \qquad (3)$$

$$X_C=\frac{1}{2\pi fC} \qquad (4)$$

B. Modelling the Thyristor Controlled Power angle Regulator

A TCPAR consist of phase shifting transformer, adjusted by thyristor switches for providing phase angle shift. In this system voltage is injected in quadrature to the line voltage using a phase shifting transformer such that resultant voltage remains same and only phase angle varies. The Fig. 3 shows principle of working of TCPAR.[11]

Fig. 3(a) shows the line diagram of TCPAR in a system. The line voltage is represented as V and the voltage injected by TCPAR is denoted as ΔV. The connection diagram of TCPAR in a three phase line is shown in Fig. 3(b). TCPAR will inject a voltage ΔV in quadrature with the line voltage, which results in an angular phase shift of σ. The vector diagram representation is as shown in Fig. 3(c).

III. SYSTEM PERFORMANCE ANALYSIS

The power system model shown in Fig.1 is implemented in laboratory for analysing oscillation. TCSC and TCPAR were designed and fabricated in the lab and transient performance evaluations of the system under four different operating conditions were analyzed. Fig.4 shows the laboratory setup of the proposed system.

The scale down model of generation plant is represented by 415V,4.5A, 3phase salient pole synchronous generator having rated per phase power of 1.5kVA. A 200MVA,220V,250Km transmission line with line impedence of 4.81Ω is trasfering power from generation plant to infinite bus.

A. Operating procedure

In the laboratory the connections are made as in Fig.4. Armature resistance of DC motor is made zero for reducing the damping torque. Using a 3-point starter the motor is operated.The motor is made to attain its synchronous speed by adjusting motor field flux. Further alternator voltage is made equal to EB bus voltage, by varying the alternator field current. Generator unit is synchronized with the infinite bus.

The power flow in the system is controlled by adjusting field current of DC motor using switch S1. When switch S1 is closed R2 is shorted, hence the field current increases and power delivered decreases. At S1 in the open position net resistance in the path becomes sum of R1 and R2, which reduces the field current and there by power generation increases. Hence rapid closing and opening of S1 will make a sudden change in power from low value to high. The power flow is sensed using a current transducer and captured in the DSO.

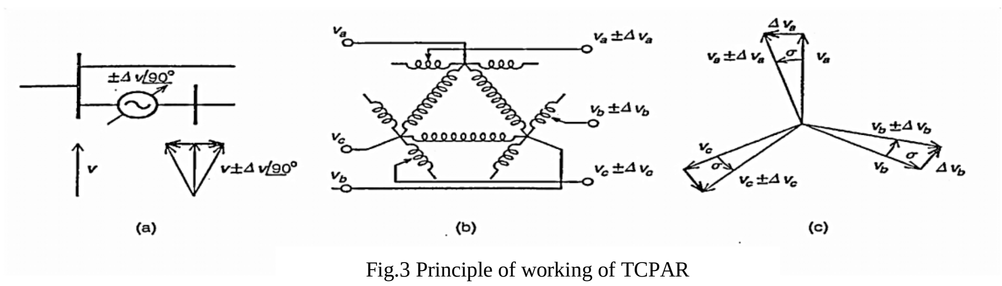


Fig.3 Principle of working of TCPAR

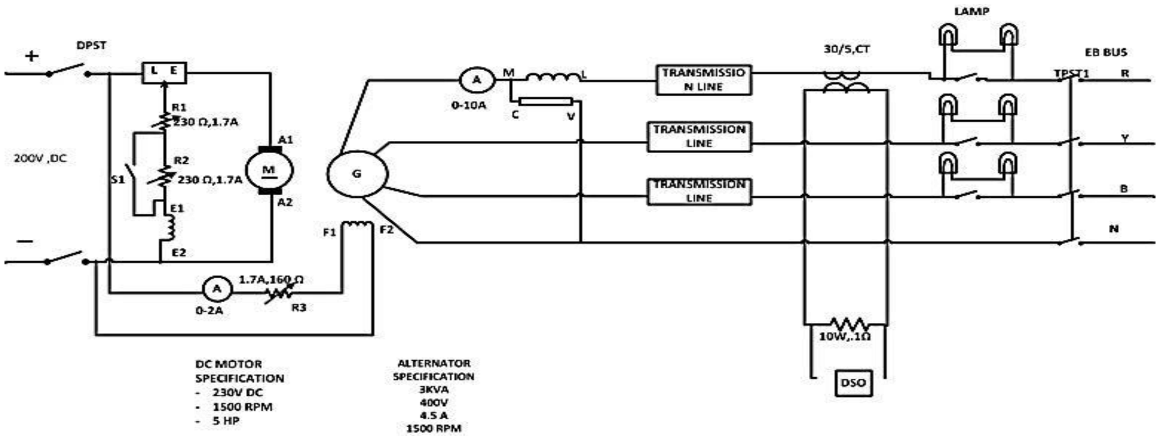


Fig .4 Laboratory model to analyse oscillation in powersystem

Many sudden disturbances like faults, sudden change in load, may cause a system to lose stability even when the system is operated below its steady state stability limit. The laboratory setup described in this paper is used to generate a sudden disturbance in the system by making a sudden change in the load. It is achieved by abruptly changing the motor field current by rapid switching of S1. This method is implemented to analyze the stability of the oscillation in the system. The analysis is done in four different cases as explained in the following sections.

B. *Case I : System performance without any FACTS devices.*

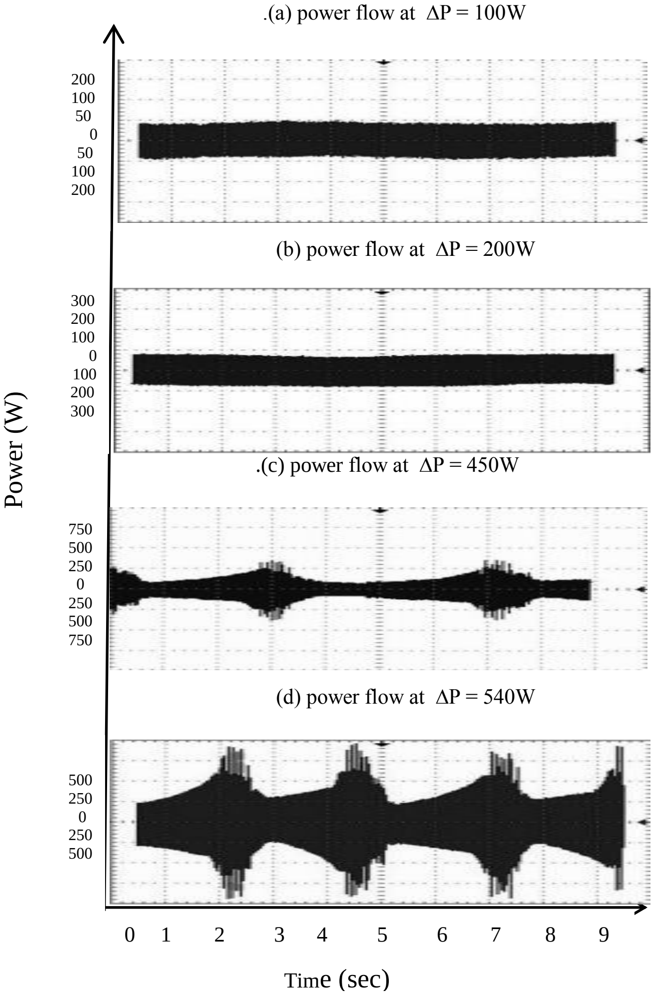
This section presents the analysis of dynamic performance of system without any FACTS devices. The laboratory setup is as shown in Fig 4. A transient disturbance of sudden load change is applied to the system, and the power flow is captured. By adjusting motor field current the range of load change is increased. Fig 5 compares the power flow on transmission line for four levels of power transfer.

It has been observed that the system become unstable for a sudden change in power above 540W per phase. Fig.5 illustrates , maximum power flow through the system without any compensation is found as 540W. The following section investigate the improvement in power flow and system damping by inclusion of FACTS devices such as TCSC and TCPAR.

C. *Case II : System performance with series connected TCSC*

In this case the system performance is analyzed by including a TCSC in series with the transmission line. The TCSC is designed for 50% line reactance compensation.
The laboratory setup is shown in Fig.6. The operating procedure is same as explained above. The range of change in load is increased by adjusting motor field flux.

.(a) power flow at ΔP = 100W



(b) power flow at ΔP = 200W

.(c) power flow at ΔP = 450W

(d) power flow at ΔP = 540W

Fig.5 Power flow at different load changes.

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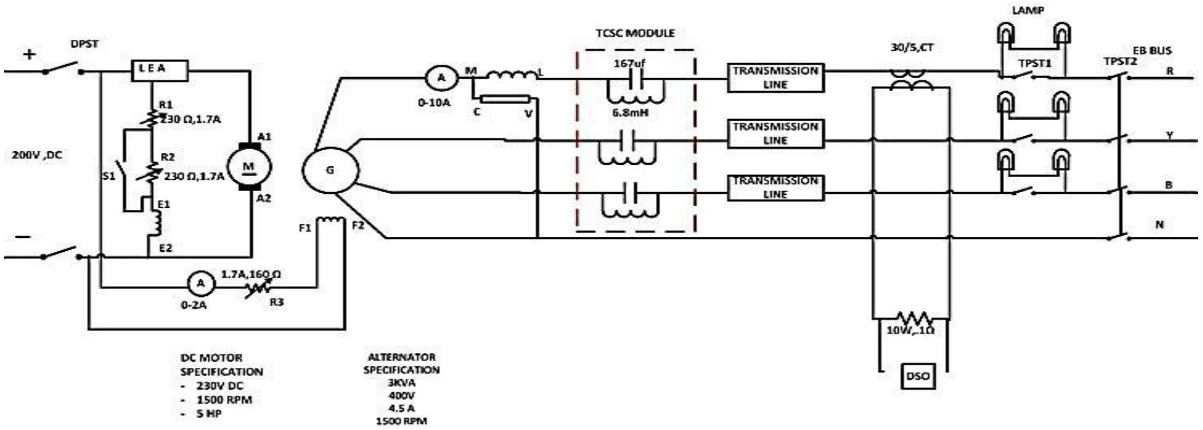


Fig. 6 System model with TCSC

i) TCSC Design [9]

The proposed system consists of a TCSC module for 50% line reactance compensation.

$$\mathrm{X_{line}} = 4.81\Omega$$

For 50% line reactance compensation

$$\mathrm{X_{TCSC}} = 2.405\Omega$$

$$X_{TCSC} = \frac{jX_c}{1-\left(\frac{X_c}{X_L}\right)} \qquad (3)$$

$$\mathrm{X_L} = \frac{\mathrm{X_C}}{9} \qquad (4)$$

$$C = \frac{1}{2\pi f X_C} \qquad (5)$$

$$L = \frac{X_L}{2\pi f} \qquad (6)$$

Hence the designed value of inductor and capacitor of TCSC for 50% line compensation is:

C=165µf.
L=6.8mH.

(ii) Performance analysis of system for different load changes.

For the performance analysis of system,power flow for a sudden disturbance of load changes are captured .A sudden load change is applied to the system by varying the motor flux.

Fig 7 shows the power flow of the system with TCSC at different load changes. The figure illustrate that the system is stable for power of 300W ,which is less than the line capacity of system without any compensation. Oscillations are created by TCSC in the system and makes it unstable. So significant damping should be provided to system whenever TCSC is in service.

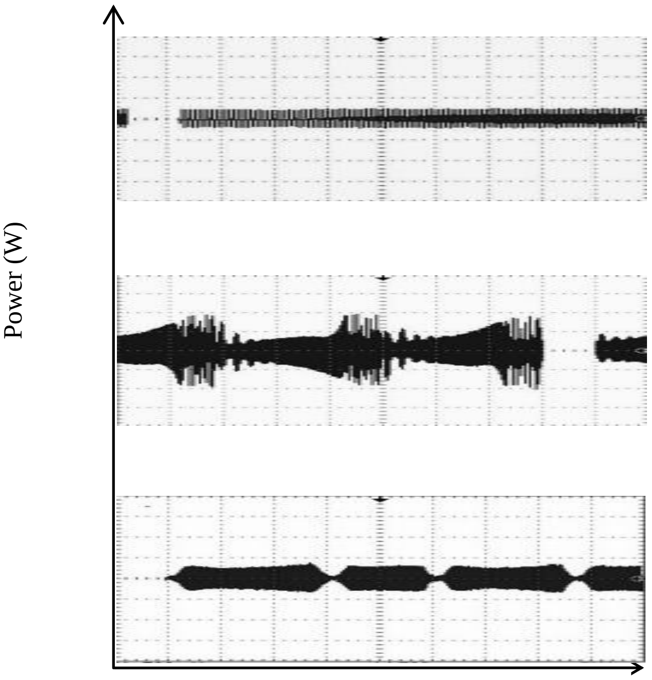


Fig.7 Power flow at different load changes.

D. Case III : System performance with series connected TCPAR

In this case the system performance is analyzed by including a TCPAR in series with the transmission line. Fig 8 shows the laboratory setup. The operating procedure is same as explained in section III A.By varying rotor field flux the range of change in load is increased.

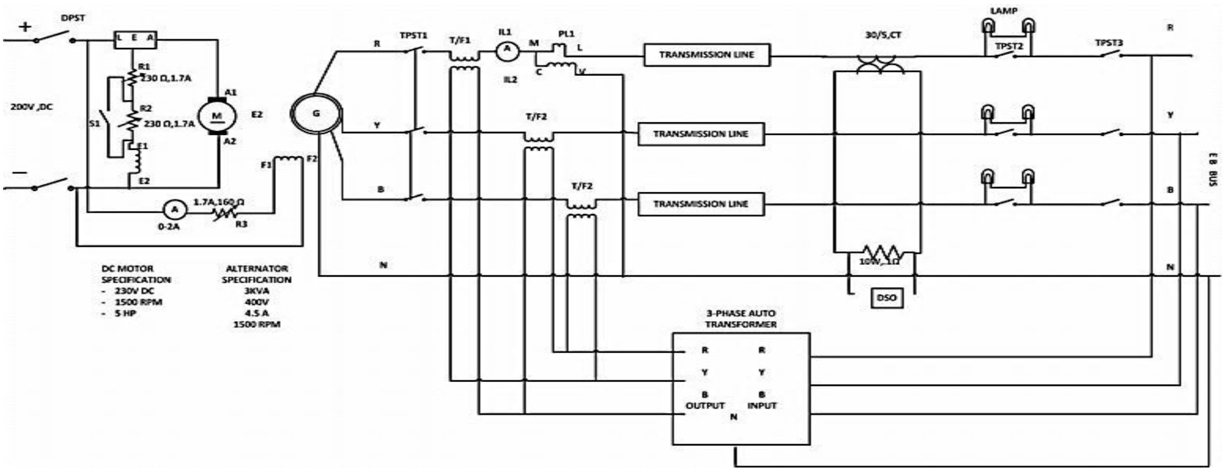


Fig.8(a) System model with TCPAR

The system is analyzed by injecting a small voltage in quadrature with the line voltage using TCPAR. The TCPAR module consists of three, single phase transformers T/F1,T/F2,T/F3 as shown in Fig 8. The primary of these transformers are connected to the three phase transmission line and secondary windings to the autotransformer.[11]

In this setup T/F1 is connected to R phase of line and its secondary is connected to YB of the autotransformer, thus the voltage injected on line should be in quadrature with the line voltage.

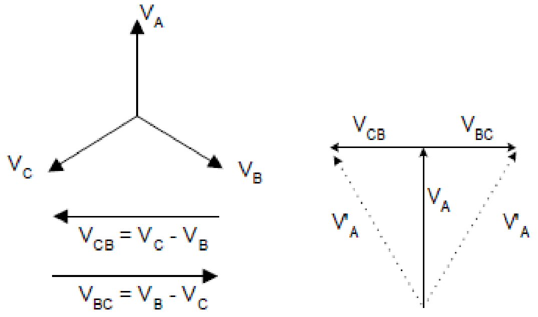
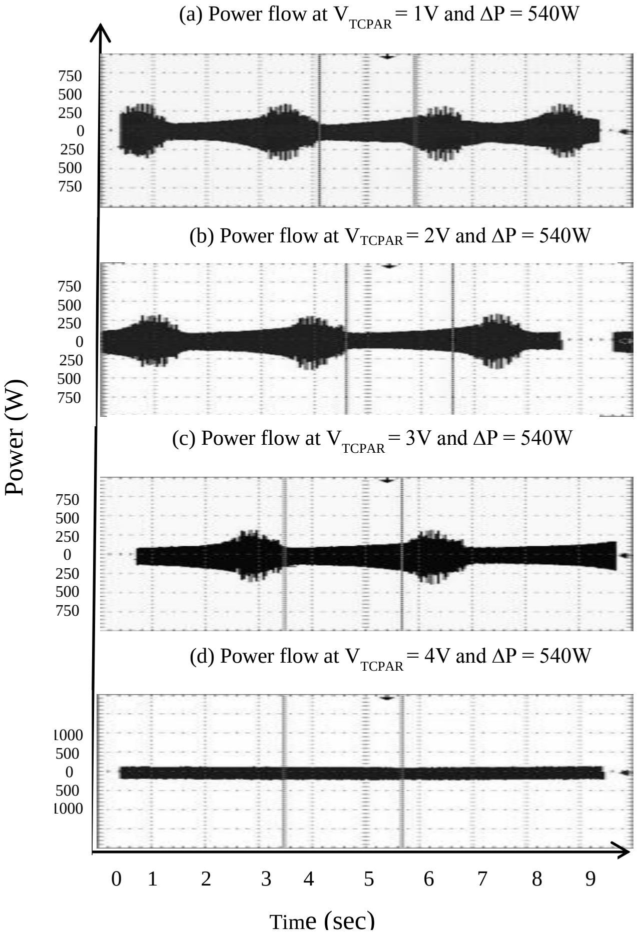


Fig.8(b) Development of quadrature voltage for phase A.

Fig.8(b) shows the vector diagram representation of development of quadrature voltage. The magnitude of injected voltage is varied by using an autotransformer. For each voltage injection, the maximum change in power that the system can transfer at stable condition keeping generator field current constant is observed.The power flow at different change in power for different voltage injection are shown in Fig 9.


(a) Power flow at $V_{TCPAR} = 1V$ and $\Delta P = 540W$

(b) Power flow at $V_{TCPAR} = 2V$ and $\Delta P = 540W$

(c) Power flow at $V_{TCPAR} = 3V$ and $\Delta P = 540W$

(d) Power flow at $V_{TCPAR} = 4V$ and $\Delta P = 540W$

Fig 9. Effect of TCPAR on power oscillation damping

The Fig 9 shows the power flowof the system for constant step load change at different voltage injection. The figure illustrates the effect of TCPAR on power oscillation damping. It is observed that the number of inter area oscillation can be reduced by increasing the voltage injection of TCPAR.Table.1 summarizes the transient test resultsshown in Fig.9.

TABLE.1

Effect of TCPAR on Power Oscillation Damping

Injected voltage V_{TCPAR} (V)	**Number of oscillations per 10sec**	**Generator field Current I_f (A)**	**Load Change ΔP (Watt)**
1	4	0.5	540
2	3	0.5	540
3	2	0.5	540
4	0	0.5	540

E. *Case IV : System performance with series connected TCSC and TCPAR*

This section presents the analysis of dynamic performance of system with series connected TCSC and TCPAR. The laboratory setup is as shown in Fig.10.The system is operated as explained in section III. A. Fig.12 illustrates system performance analysis for a sudden change in load for different power levels.

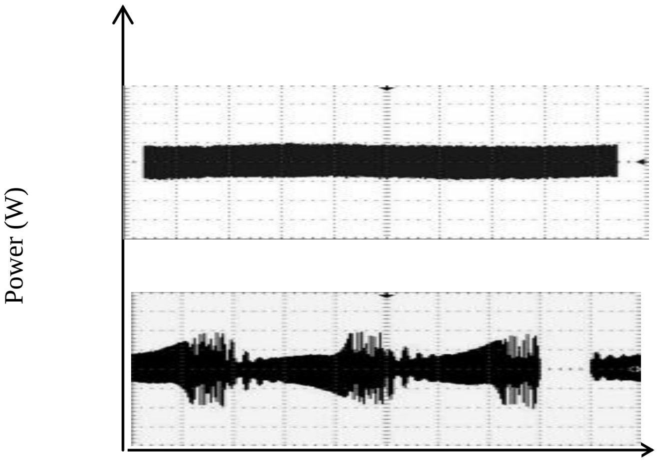


Fig.11 Power flow at different load changes

The plots show that the power flow of the system is increased from 340W to 1200W and stability is preserved. Fig.11 illustrate the enhanced power transfer capabilities over a wide range of operating condition due to the addition of TCSC and TCPAR. It is summarized as maximum power flow is achieved when both TCSC and TCPAR are coordinately controlled.

IV. RESULTS

Fig.12 compares the power flow on the transmission line for a step load disturbance of 540W at four different cases. The cases present in this section summarize the system dynamic performance and illustrate the enhanced power transfer capability over a wide range of operating condition due to the addition of series connected two FACTS devices, TCSC and TCPAR.

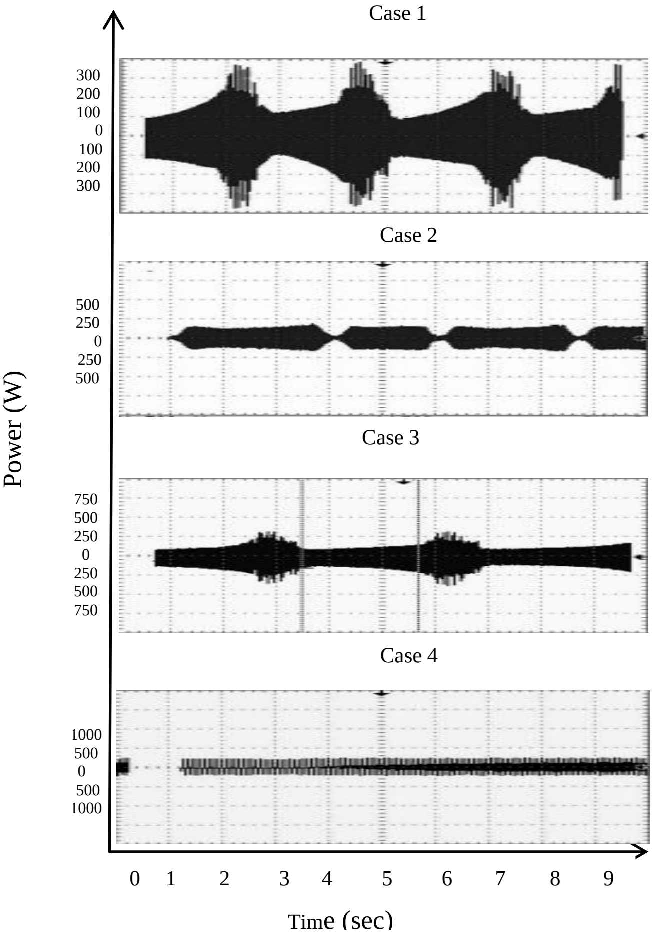


Fig.12 Power flow of four cases for a load change ΔP=340W.

Case 1 : System model without FACTS device
Case 2 : System model with TCSC.
Case 3 : System model with TCPAR.
Case 4 : System model with coordinate control of TCSC and TCPAR.

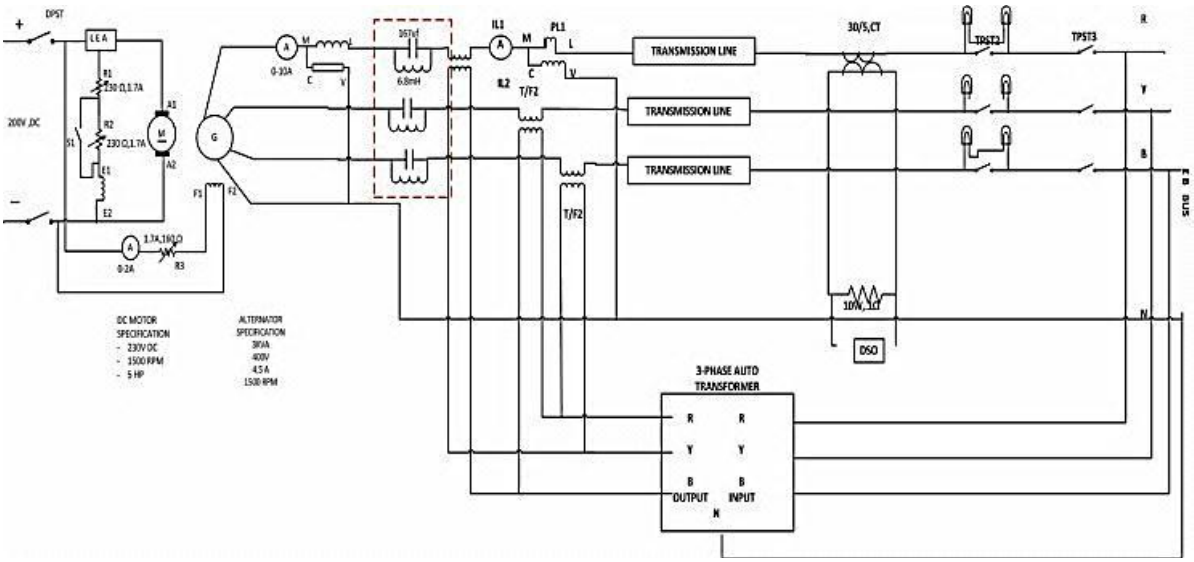


Fig.10 System model with TCSC and TCPAR

I. CONCLUSION

In this paper design and hardware implementation of the proposed system with series connected FACTS devices is presented and discussed. Performance of the system is analyzed in four different cases. The result of thisinvestigation shows that coordinated control of TCSC and TCPAR are essential for the enhancement of stability and to improve power transfer capability.

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