Power Flow and Stability Improvement in Distribution Systems Using Phase Angle Regulator

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Abstract. The increased penetration of renewable power resources into power grid leading to more stability and security issues in the grid. The dynamic power flow control as per system requirements is highly desirable in order to ensure the system security. The congested management and power flow control can be achieved with FACTS Controllers. One among the FACTS devices is the Phase Angle Regulator (PAR), which is used in the article for controlling the power flow and system stability. The power and control circuits of the PAR has been developed in Maltlab Simulink environment and has been simulated with domestic, commercial and distribution systems with phase angle control and results have been presented in the article. The control logic has been developed to improve the power flow with automatic switching action of PAR for the desired power flow in a feeder. Finally laboratory based testing have been performed without and with PAR with different phase angles and loads such as small, medium and heavy loads and results have been presented herewith and which proves the effectiveness of PAR in improving power transfer capability and stability.

Keywords: Power flow control · Phase Angle Regulator · Power system stability · Congested management · Power system security · FACTS devices · Phase shifting transformer · Zigzag transformer

1 Introduction

In the present scenario the rise of power demand leads to interconnection of power system for various reasons like reducing economical cost and to enhance reliability of the system. It leads to growing complexity which will cause further system collapse due to major outages.

Power flow control and congested management playing a crucial role in power system security and power restoration process. Phase Angle Regulator (PAR) can be widely used in the low marginal control of power especially in commercial and distribution systems. The PAR is used to control the phase angle between two buses, which are interconnected with a transmission line or feeder. This alteration of the phase angle leading to the variation of load angle and subsequently the power flow and congested management in the system. In this work the test systems of domestic, commercial and

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distribution systems have been developed to carry out the simulation and testing. The developed systems have been simulated without and with PAR and presented the results. The domestic system is experimentally tested in the laboratory and results have been presented and prove the effectiveness of the PAR [1–6].

2 Power System Stability and Congested Management

Power system stability is defined as a system ability to regain its initial equilibrium state after being subjected to a disturbance and its classificationare given in Fig. 1.

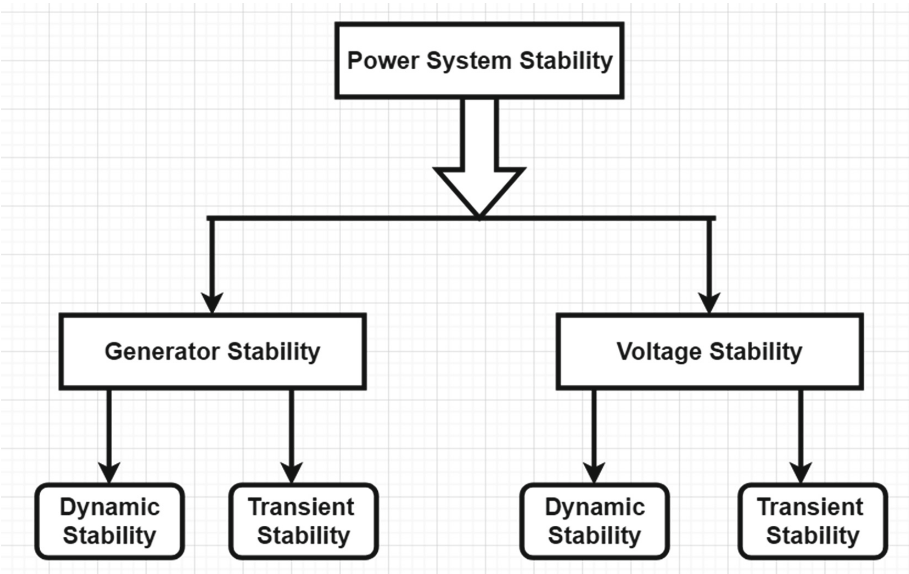

Fig. 1. Power system stability stratification

2.1 Rotor Angle Stability

The system should remain in synchronism even after being subjected to the disturbance, which involves output power oscillates reflected in rotor oscillations.

2.1.1 Relation Between Power and Angle

Relation between the power and angular position of a rotor in synchronous machine is nonlinear relation, when the synchronous generator is feeding a synchronous motor through transmission line. The power transferred to the motor from the generator is depends on the function of angular displacement between rotors of the generator and motor this is because of Motor internal angle, generator internal angle, and the angular displacement between motor and generator terminal voltage and power flow is given by the Eq. 1.

$$P_{12} = \frac{V_1 V_2}{X_{12}} \sin\delta \tag{1}$$

This equation say that the power transferred to a motor from generator is maximum when the angle is 90°, if the angle is further increased beyond 90°, power transferred starts decreasing is shown in Fig. 2. The maximum power transferred is directly proportional to machine internal voltage [5–10].

$$P_{12max} = \frac{V_1 V_2}{X_{12}} \tag{2}$$

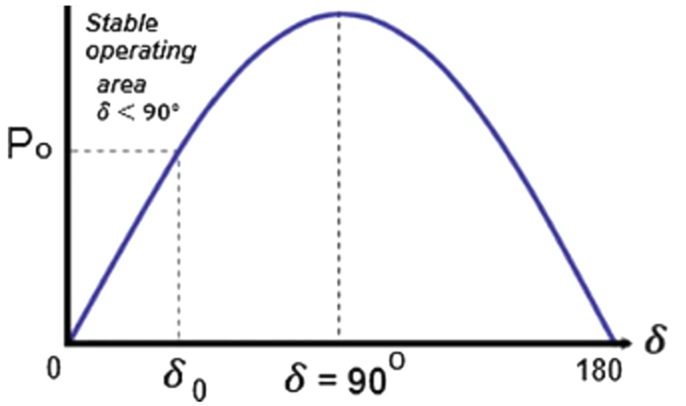

Fig. 2. Power angle curve

2.2 Congested Management

The congested management of the power system is related to the KVA or MVA capacity of the lines or feeders in the ring main distribution system and Transmission Systems. The Fig. 3 illustrating the need of Congested Management since some of the lines are carrying its power to its maximum MVA limit nearly 100%. These situations can be well managed with the use of PAR in both kinds of systems such as distribution as well as transmission systems [11–14].

3 Phase Angle Regulator

The Phase Angle Regulator (PAR) or Phase Shifting Transformer (PST) is a power full device in maintaining the congested management and power flow control in electrical systems. Figure 4 is illustrating the Single line diagram of the test system with PAR, it comprised of a generating source, feeder connected to the PAR, which feeds the load.

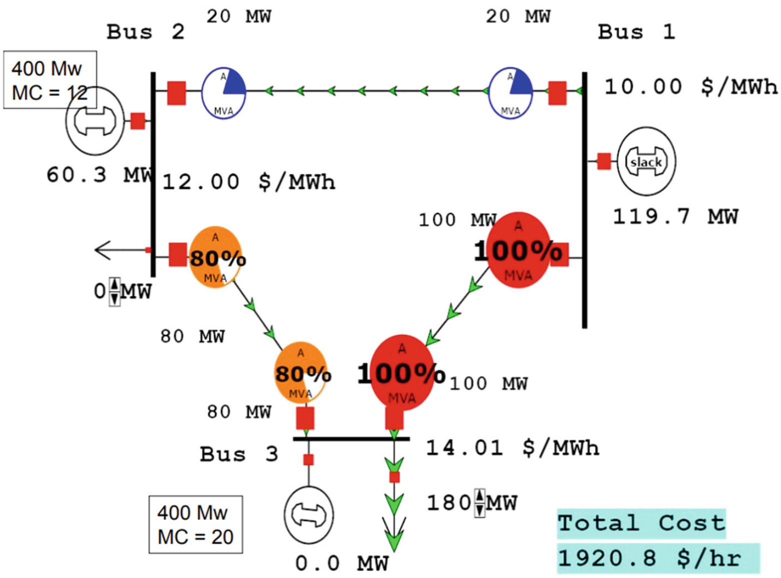

Fig. 3. System single line diagram without congested management

Figure 5 depicts the equivalent circuit of the system without PAR and Fig. 2 shows the corresponding power angle curve without compensator. Figure 6 illustrating the Phase Angle Regulator (PAR) (a) equivalent circuit (b) Power circuit (c) Phasor diagram. Figure 7 depicts the Phase Angle Regulator (PAR) (a) Single line diagram (b) Phasor diagram (c) Power angle curve.

The power transfer without PAR is expressed in the Eq. (1) and maximum allowable power without PAR in a system as expressed in Eq. (2) respectively. The Eq. (3) showing the equivalent bus voltage with PAR in terms of original bus voltage and equivalent injected voltage of PAR, corresponding Eqs. (4), (6) shows the improved power with its expressions and (5) reactive power of the system. Figure 8 illustrates the phasor diagram and power angle characteristics with different phase angles and Fig. 9 depicts the transient stability improvement with PAR [1–5].

$$V_{1eff} = V_1 + V_\sigma \tag{3}$$

$$P_{12} = \frac{V_1 V_2}{X_{12}} \sin(\delta \pm \sigma) \tag{4}$$

$$Q_{12} = \frac{V_1 V_2}{X_{12}} [1 - \cos(\delta \pm \sigma)] \tag{5}$$

$$P_{12} = \frac{V_1 V_2}{X_{12}} [\sin\delta + \frac{V_\sigma}{V_2} cos(\delta) \tag{6}$$

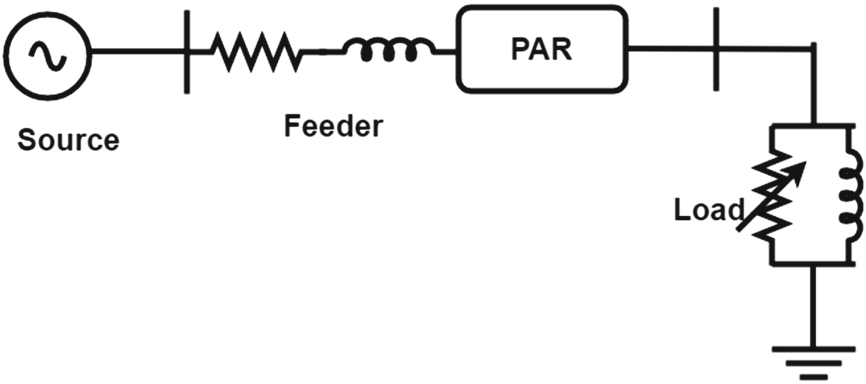

Fig. 4. Single line diagram of the test system with PAR

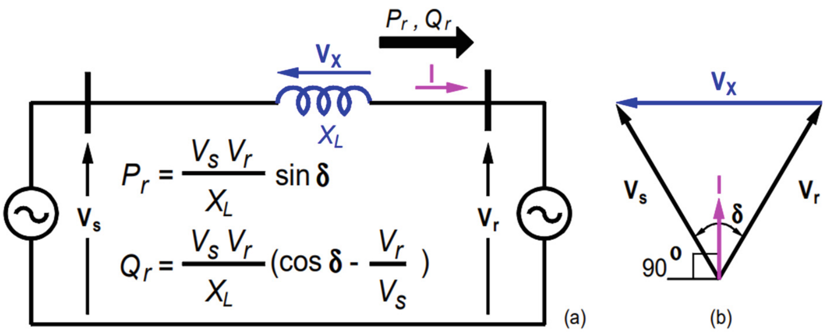

Fig. 5. Equivalent circuit of the system without PAR

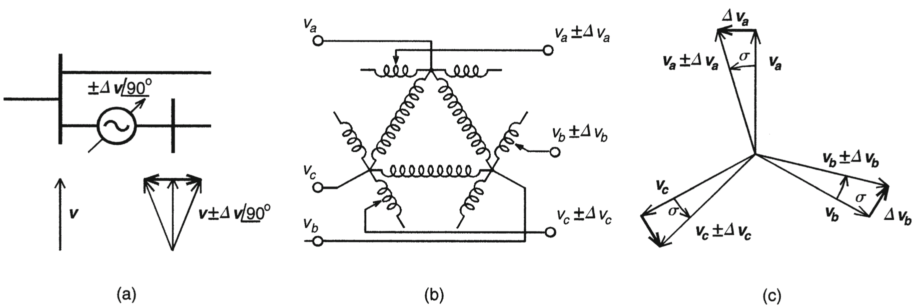

Fig. 6. Phase Angle Regulator (PAR) (a) Equivalent circuit (b) Power circuit (c) Phasor diagram

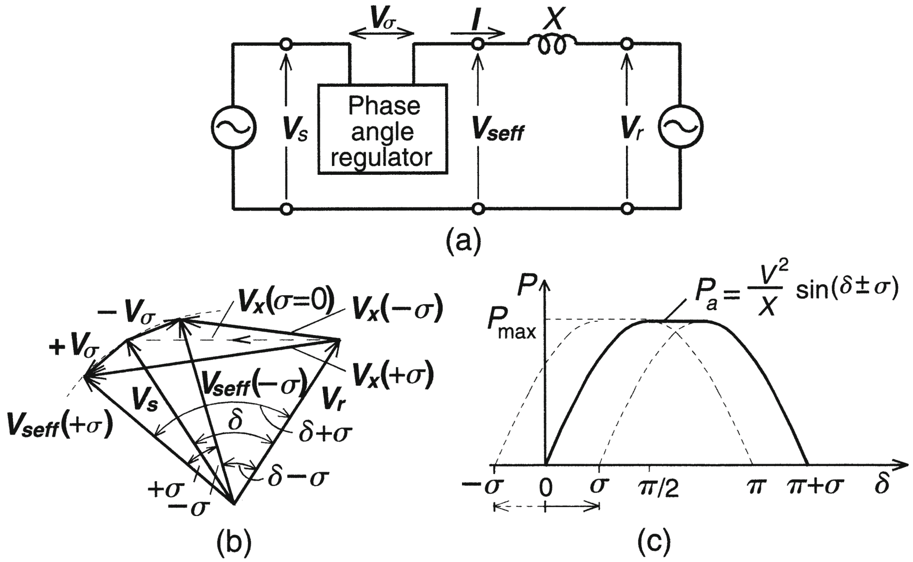

Fig. 7. Phase Angle Regulator (PAR) (a) Single line diagram (b) Phasor diagram (c) Power angle curve.

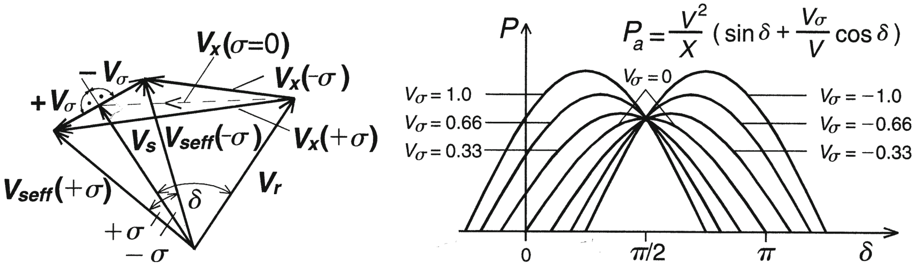

Fig. 8. Phasor diagram and power angle characteristics with different phase angles

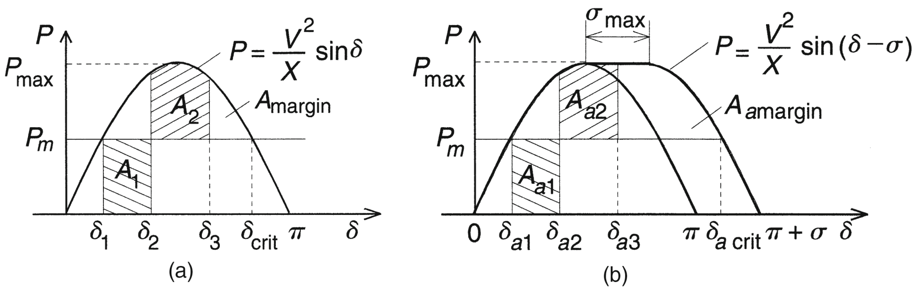

Fig. 9. Transient stability improvement with PAR

4 Case Study and Results

The test system is developed in the Matlab Simulink environment as Fig. 10 illustrates the Simulink Model of PAR including closed loop control circuit being simulated and results have been presented herewith. Table 1 depicts the Power Transfer in 230 V Domestic System without and with PAR simulation results. The results of domestic system with variation in phase angle of PAR showing the credibility of the PAR on power flow control and stability improvement.

4.1 The Test Results of 230 V Domestic System

The test results of 230 V Domestic system being presented with, Table 2 depicts the Power Transfer in 230 V Domestic System without PAR experimental results, and Table 3 illustrates the Power Transfer in 230 V Domestic System without PAR experimental results for small loads. Table 4 spectacles the Power Transfer in 230 V Domestic System without PAR experimental results for medium loads and Table 5 prospects the Power Transfer in 230 V Domestic System without PAR experimental results for large loads. Figure 12 shows the 230 V Practical System with PAR with angle variation for small loads, Fig. 13 illustrates the 230 V Practical System with PAR with angle variation for medium loads and Fig. 14 encapsulates the 230 V Practical System with PAR with angle variation for heavy loads (Fig. 11).

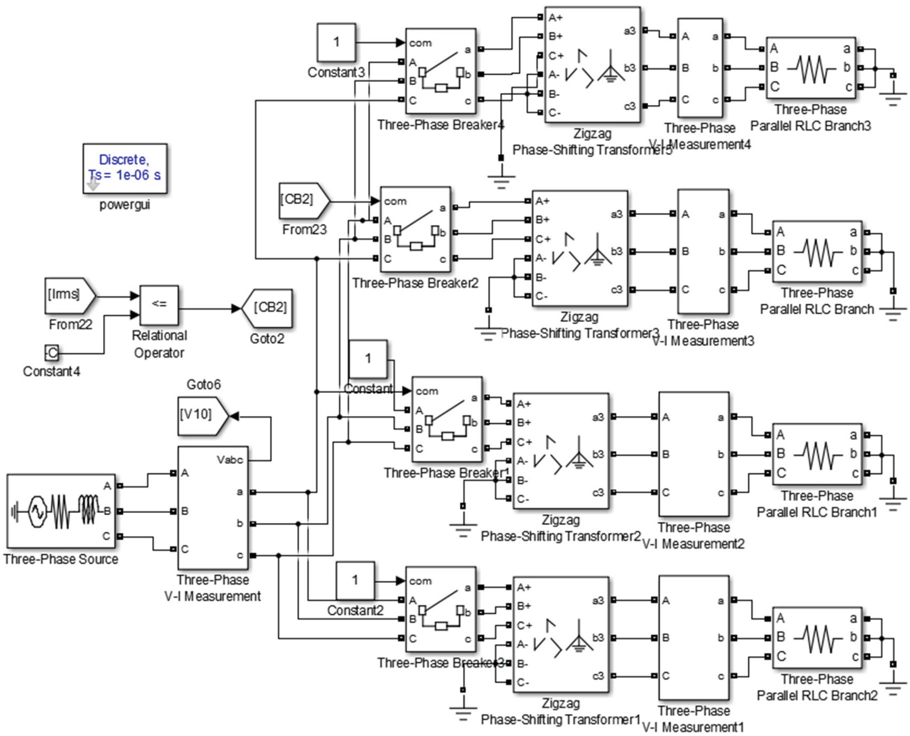

Fig. 10. Simulink Model of PAR including closed loop control circuit

Table 1. Power Transfer in 230 V Domestic System without and with PAR simulation results

S. No.	Power Transfer without PAR P in W	Power Transfer with PAR P in W
1	530	1340

Table 2. Power Transfer in 230 V Domestic System without PAR experimental results

S. No. Load	Voltage in V	Current in A	Power in W
1	228	3.8	750
2	225	6.7	1125
3	224	8.3	1200

Table 3. Power Transfer in 230 V Domestic System without PAR experimental results for small loads

S. No. Phase Angle	Voltage in V	Current in A	Power in W
1	196	1	368
2	198	1	380
3	200	1	400

Table 4. Power Transfer in 230 V Domestic System without PAR experimental results for medium loads

S. No. Phase Angle	Voltage in V	Current in A	Power in W
1	182	1.38	468
2	186	1.4	488
3	188	1.42	496

Table 5. Power Transfer in 230 V Domestic System without PAR experimental results for large loads

S. No. Phase Angle	Voltage in V	Current in A	Power in W
1	170	1.6	520
2	174	1.68	552
3	176	1.7	560

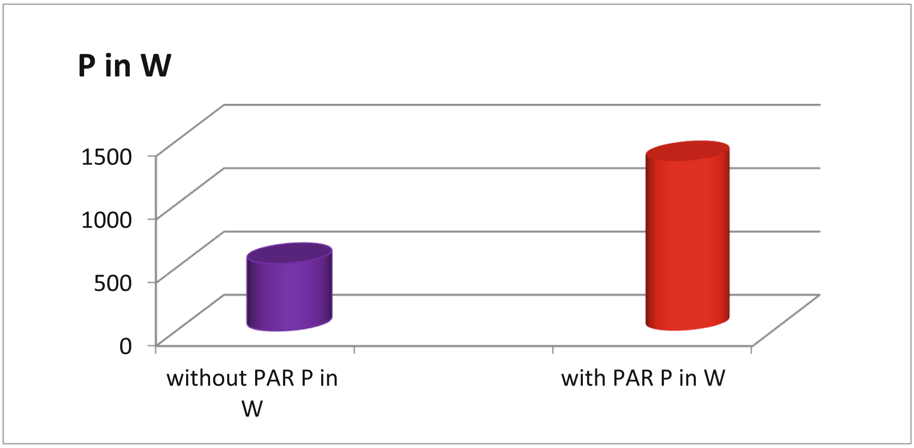

Fig. 11. Power flow without and with Phase Angle Regulator in domestic system

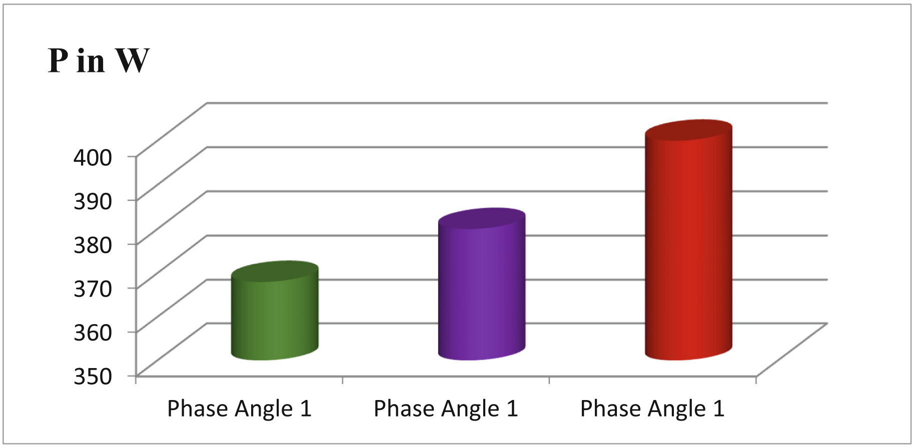

Fig. 12. 230 V Practical System with PAR with angle variation for small loads

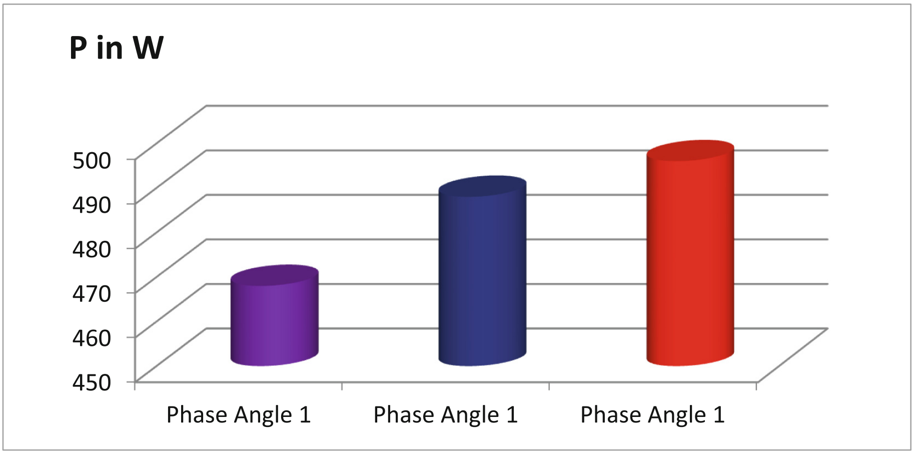

Fig. 13. 230 V Practical System with PAR with angle variation for medium loads

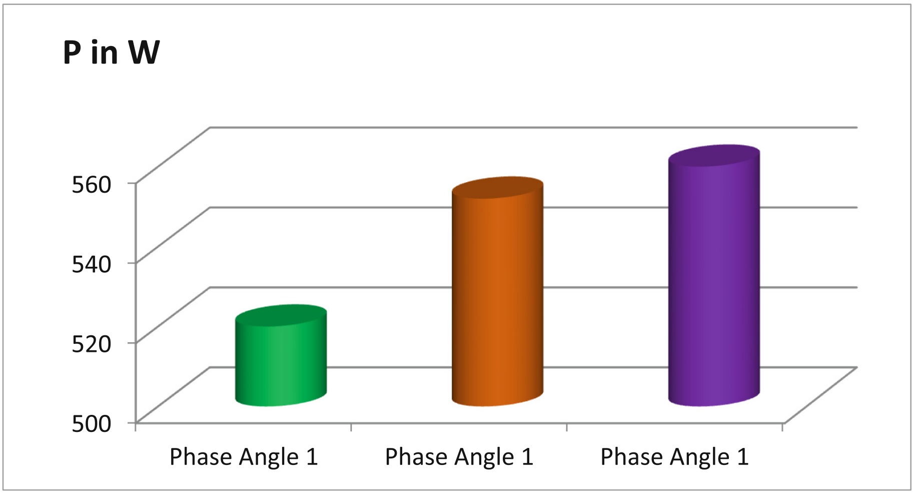

Fig. 14. 230 V Practical System with PAR with angle variation for heavy loads

4.2 The Test Results of 415 V Commercial System

The test results of 415 V Commercial system have been presented herewith as Fig. 15 shows the Power transfer through the feeder in commercial system for load 1 with different phase angles, Fig. 16 illustrates the Power transfer through the feeder in commercial system for load 2 with different phase angles. Table 6 indicating the Power Transfer in 415 V Commercial System Results with PAR, Fig. 15 prospects the Power transfer through the feeder in commercial system for load 1 with different phase angles, Fig. 16 encapsulates Power transfer through the feeder in commercial system for load 2 with different phase angles and Fig. 17 illustrating the Power transfer through the feeder in commercial system for load 3 with different phase angles. All these results proves the effectiveness of PAR in power flow control and stability enhancement of the commercial system with power angle control.

Table 6. Power Transfer in 415 V Commercial System Results with PAR

S. No. Phase Angle	Power Transfer without PAR P in KW	Power Transfer with PAR angle1 P in KW	Power Transfer with PAR angle2 P in KW
1	0.099	0.202	0.231
2	1.104	2.066	2.146
3	10.83	14.2	–

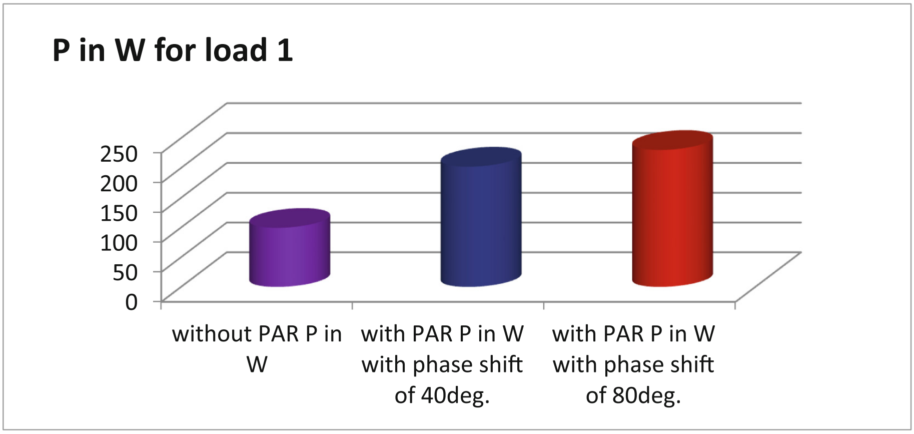

Fig. 15. Power transfer through the feeder in commercial system for load 1 with different phase angles

4.3 The Test Results of 11 KV Distribution System

The test results of 11 KV Distribution system have been presented herewith as Table 7 shows the Power Transfer in 11 KV Distribution System results with PAR, Fig. 18 illustrates the Power transfer through the feeder in distribution system for load 1 with different phase angles. Figure 19 prospects the Power transfer through the feeder in distribution system for load 2 with different phase angles and Fig. 20 encapsulates the Power transfer through the feeder in distribution system for load 3, all these results have been indicating that the power angle control made with PAR is most effective in improving the Power Transfer and system stability improvement for all kinds of systems such as domestic, commercial as well as distribution systems.

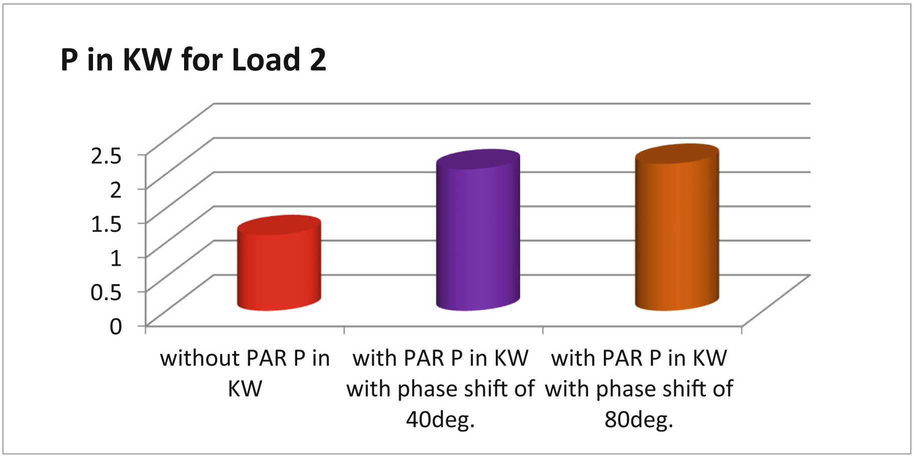

Fig. 16. Power transfer through the feeder in commercial system for load 2 with different phase angles

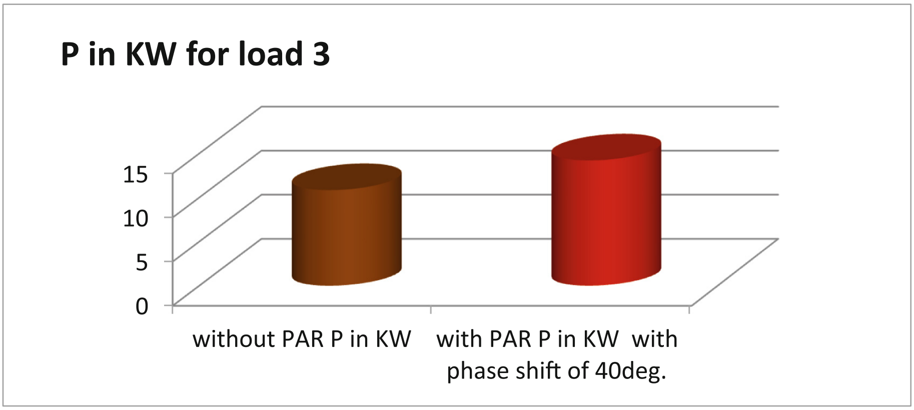

Fig. 17. Power transfer through the feeder in commercial system for load 3 with different phase angles

Table 7. Power Transfer in 11 KV Distribution System Results with PAR

S. No. Phase Angle	Power Transfer without PAR P in KW	Power Transfer with PAR angle1 P in KW	Power Transfer with PAR angle2 P in KW
1	70.8	143.3	162.2
2	863.2	1480	1530
3	7630	10060	–

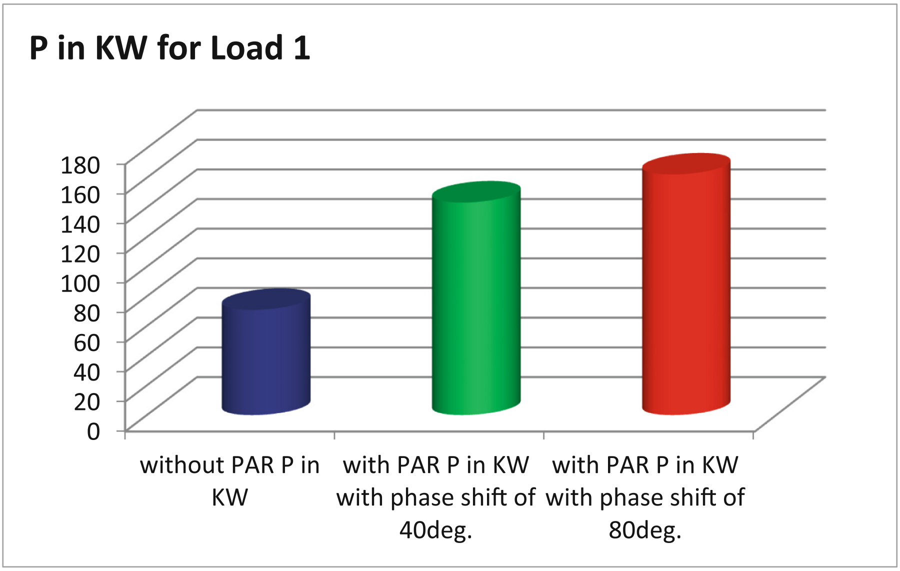

Fig. 18. Power transfer through the feeder in distribution system for load 1 with different phase angles

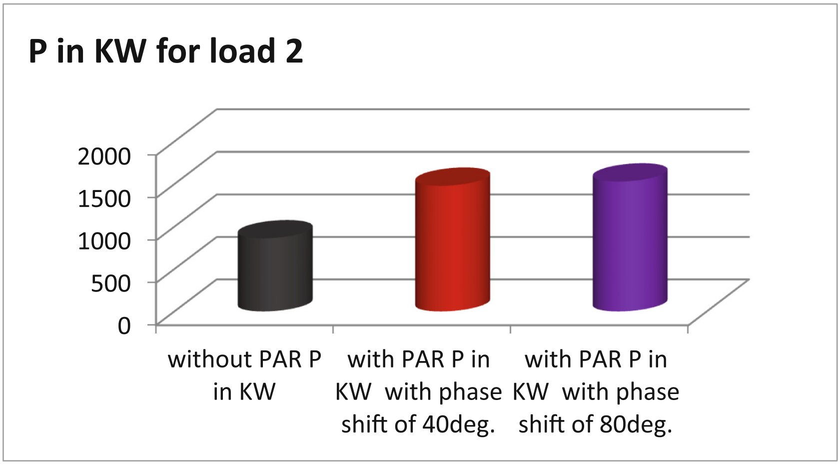

Fig. 19. Power transfer through the feeder in distribution system for load 2 with different phase angles

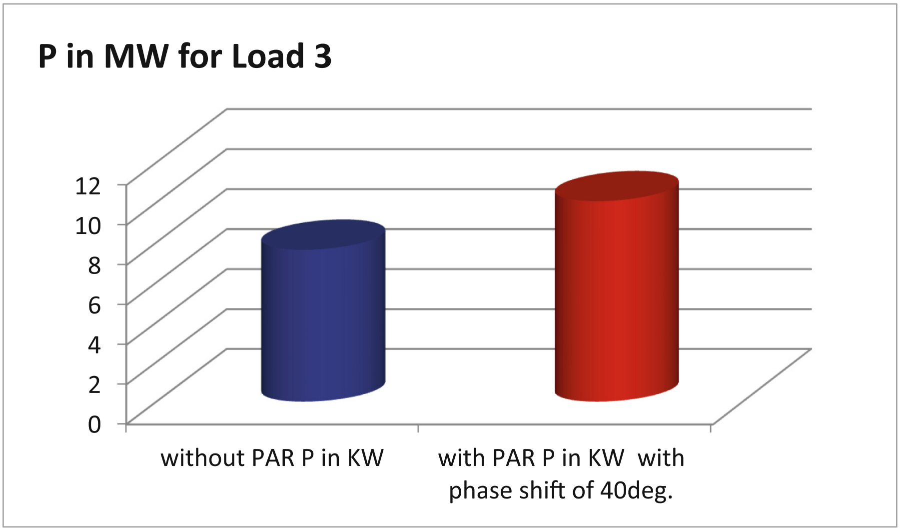

Fig. 20. Power transfer through the feeder in distribution system for load 3

5 Conclusions

The power and control circuits of the PAR has been developed in Maltlab Simulink environment and has been simulated with domestic, commercial and distribution systems with phase angle control and results have been presented in the article. The control logic has been developed to improve the power flow with automatic switching action of PAR for the desired power flow in a feeder. Finally laboratory based testing have been performed without and with PAR with different phase angles and loads such as small, medium and heavy loads and results shows the effectiveness of PAR in improving power transfer capability and stability. The test results of all three systems such as domestic, commercial and distribution systems have been presented in the article. The simulation and experimental test results of domestic system with different power angles proves the effectiveness of the PAR on power flow and system stability. The simulation results of both commercial and industrial systems shows the significant improvement in power transfer capability and system stability with the control of power angle.

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