Loading Balance of Distribution Feeders with a Generic Loop Power Flow Controller

Tahir Mahmood [1], Salman Zafar [2], Hasham Khan[3], Faisal Masood [4] Jamil Ahmad Khan [5]

[1,2,4.] Department of Electrical Engineering, University of Engineering & Technology, Taxila 47050, Pakistan
[3.] Department of Electrical Engineering, GCT, Abbottabad, Pakistan
[5] Department of Electrical Engineering, CIIT, Abbottabad, Pakistan
tahir010@yahoo.com

Abstract: For effective operation of distribution networks, balance loading on distribution feeders has a great significance for minimizing power losses and mitigating overloading. In this paper, a Loop Power Controller (LPC) strategy is proposed for the control of active and reactive power by adjusting voltage ratio and phase shift so that balance loading on adjacent feeders can be obtained. For this purpose, back-to-back (BTB) converter, based on Voltage Source Converters (VSC) is developed and used for the management of the bidirectional transference of active power and reactive power between two independent load serving distribution feeders. The performance of the BTB converter for power flow control is demonstrated through simulation and experimental results by replacing open tie switch with BTB converter at open point in between the two adjacent feeders of a local utility system. Simulation results indicate that balance loading can be achieved in distribution feeders with loop power controller according to the variation of power loading of the two feeders.

[Mahmood T, Zafar S, Khan H, Masood F. **Loading Balance of Distribution Feeders with a Generic Loop Power Flow Controller**. *Life Sci J* 2013; 10(4):2703-2713] (ISSN: 1097-8135). http://www.lifesciencesite.com. 362

Key Words: Distribution Feeder, Loop Power Controller, FACTS Devices, PWM Control

1. Introduction

Today's Electric power systems are highly sophisticated and requires a careful design of new devices especially for transmission and distribution systems in new deregulated electricity markets with taking into consideration the existing equipments. However this is not an easy task due to the economical and environmental issues that limits the power engineer's approach. So this requires a review of conventional techniques and adaption of new concepts for the effective use of existing power system resources without reduction in system security and stability. Electric Power Research Institute (EPRI) in 1980 proposed a new approach to sort out the problem of designing and operating power systems that is known as Flexible AC Transmission Systems (FACTS) [1]. The two main purposes of FACTS are to enhance the transmission system capacity and control power flow over specified transmission routes. The developments in the field of power electronics have had major impact on the deployment of proposed concept. With the improvements of Gate Turn off (GTO) thyristor ratings, a new generation of FACTS controllers has emerged. These controllers are based on voltage source converters and include devices such as Static Synchronous Compensators (STATCOMs), Static Var Compensators (SVCs), the Static Synchronous Series Compensators (SSSCs), Thyristor Controlled Series Compensators (TCSCs), and the Unified Power Flow Controllers (UPFCs).

Renewable energies such as the PV system, Wind energy system and the utilization of Cogeneration Systems are expected to improve the efficiency of energy applications [1]-[2].Therefore in future a lot of distributed generations (DGs) will be connected to distribution networks. When the DGs are installed for feeder imbalance, it is difficult to maintain a proper voltage range [3]-[6]. In such cases, it is known that loop or mesh distribution systems are required for the balanced power flow and voltage regulation. However, this will increase the short circuit current level in the distribution system, and a method for detecting the location of faults in loop distribution systems has not yet been established. By using back to back converters, a loop power flow controller should control distribution systems without any increase in short circuit current level. Therefore, we proposed a PWM based loop power flow controller for the balance of active and reactive power in distribution systems.

In this paper, a generic loop power flow controller has been developed that transfers the load in term of active and reactive power. Two different feeders of a particular utility have been selected for case study for one full day. The load curves have been considered to equate and to balance the load between feeders. The simulated results show that the developed LPC transfers the load effectively and efficiently. As a result, the load curve of both the feeders becomes smooth.

1.1 Flexible Alternating Current Transmission Systems

According to the IEEE definition, FACTS is defined as "The Flexible AC Transmission System

(FACTS) is a new technology based on power electronic devices which offers an opportunity to enhance controllability, stability and power transfer capability of AC Transmission Systems".

1.1.1 Introduction to FACTS controllers

The broad prospective of Flexible AC Transmission Systems (FACTS) are to improve the power transfer capability and controllability of interconnected ac power systems by means of power electronic based controlled compensators. The main application of FACTS devices is to provide direct control over the amount of power flowing in a particular transmission line, or group of lines, in an interconnected AC system. This application has variously been described as power flow control, power scheduling, or closed-loop control of AC power flow. Such closed loop control of power flow in an AC system can provide a number of possible benefits such as preventing unwanted loop flows in an interconnected system, preventing inadvertent overloading of lines, allowing power to be directed along a "contract" path in a transmission system. The controllers that are designed based on the concept of FACTS technology to improve the power flow control, reliability and stability are known as FACTS controllers. These controllers were designed depending on the power system problems. Each controller has specific properties, some of them are capable of addressing multiple issues and some of them are only for a particular problem. The whole family of these controllers is depicted in figure 1. These are generally classified as 1st, 2nd and 3rd generation FACTS.

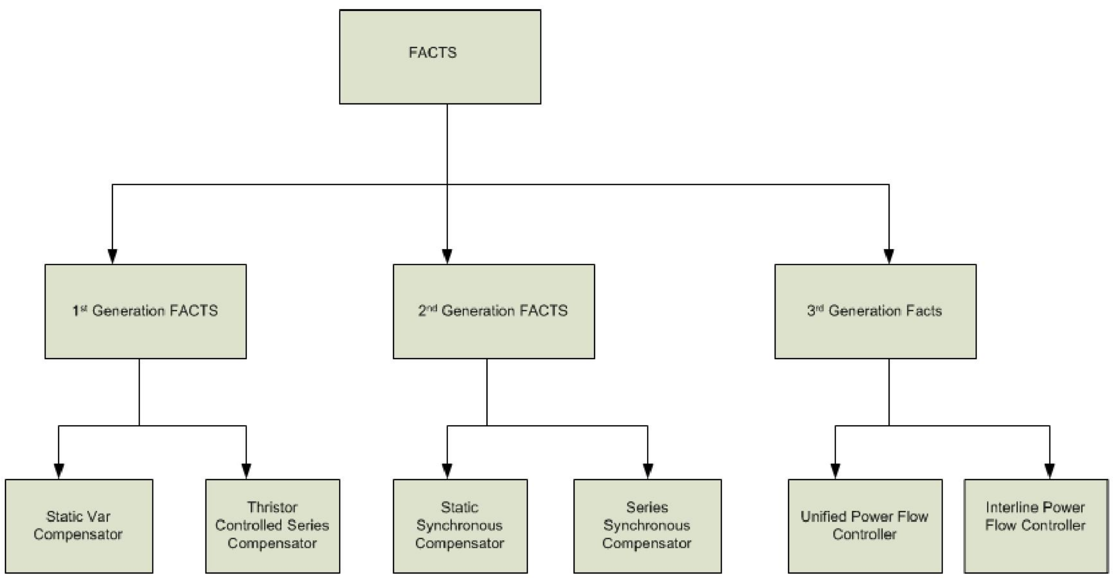

Figure 1: Classification of FACTS Devices

A wide variations of power flow controller based on FACTS have been deployed by many researchers. In [7] a fault current limiter and superconducting power flow controller is proposed by Hayakawa, N., which can not only control power flow in the steady operating state, but also has the capability to limit fault current in the faulty conditions. S.Sreejith, *et al.,* proposes a methodology based on installation cost for locating the optimal position of interline power flow controller (IPFC) in a power system network [8].S Pedakotaiah, et al., in [9] described steady-state responses and control of power in transmission line equipped with FACTS devices. R. Pillay Carpanen in [10] presents an innovated method of designing a closed loop AC power flow controller.

2. Basic Concept and Structure of Loop Power Controller (LPC)

The basic concept of the distribution system using the Loop Power Controller is as follows [4].

- Aims for free access to a distributed power supply.
- System response flexibly to unbalanced loading between feeders, and makes efficient use of equipment.
- To enable this, the system is constructed in the shape of a loop from a radial.
- A loop distribution system is provided without modifying existing systems such as the protection system, except for some loop points.

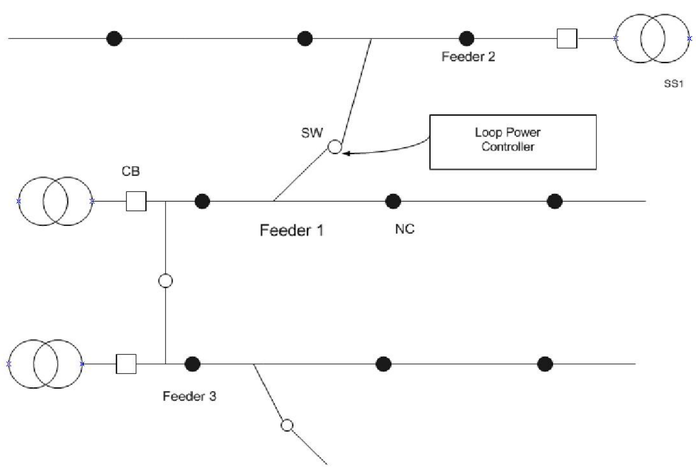

Figure 2: Radial distribution network with loop power controller (LPC)

2.1 Loop Distribution Network

Unbalance feeder loadings and concentrated grid connections of distributed generation in distribution systems are the causes of voltage disturbance of feeders. Therefore balance loadings are required to maintain suitable voltage in radial distribution systems. Figure 2 shows the radial distribution network feeding from different distribution substations. A feeder is divided into different sections by means of circuit breakers, open and closed switches. The open switches provide flexibility in case of faulty conditions. These radial systems can be converted into loop system by closing the open switches. Here we consider open switches as the installation points of LPC for load balancing that are also shown in figure 2 [12]. So the feeders are interconnected by means of LPC to mitigate power flow according to the available capacity. Normally, we targeted 1/3 of the capacity of the feeder as the standard for the LPC.

2.2 Control Method for LPC

For voltage regulation and power flow control of distribution network, one idea is to use the local voltage information at different feeding points. Theoretically voltage of power system is controlled by the reactive power. However here we would focus on the line resistance of distribution lines close to line inductive reactance.

The voltage of the two distribution feeders is obtained as local information, when LPC is installed at normally open switch in between the feeders. The voltage V_i, V_j of the two feeders and their phase difference are taken as shown in figure 3. Through the voltage control of a transformer located at distribution substation, the sending end voltage of feeders is managed [11]. The difference between the loads of the two feeders is observed as a voltage difference at a normally open switch and using this information LPC controls the power flow in between the feeders.

Figure 4 shows the equivalent circuit of loop power controller. In this figure the installation point of controller and points (V_{xi}, and V_{xj}) to control is depicted. The voltage of the control point is presumed as follows from the impedance ((R_i, X_i), (R_j, Xj)) of the distribution line from the LPC of feeder 1 and feeder 2 to the control point, the power flow (**P_{Lpcij}**) of LPC, the reactive power (**Q_{LPCij}**) and the local voltage (V_i, Vj) as given in the following equations.

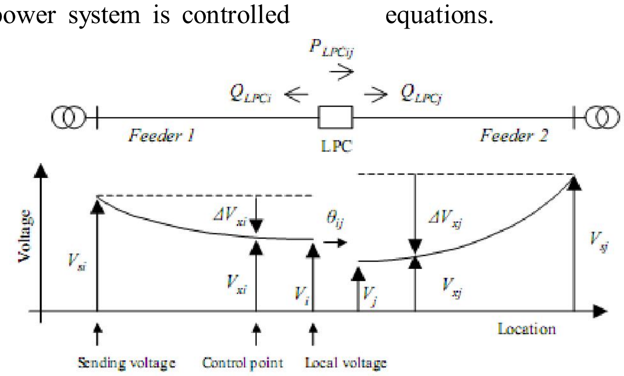

Figure 3: Control Parameters of Loop Power Controller (LPC) [11]

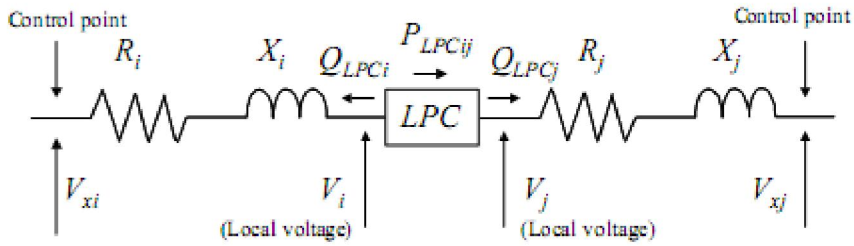

Figure 4: Equivalent Circuit of Loop Power Controller (LPC)

$$V_{xi} = v_x\left(V_i, P_{LPCij}, Q_{LPCi}, R_i, X_i\right) \quad (1)$$

$$V_x = v_x\left(V_j, -P_{LPCij}, Q_{LPCj}, R_j, X_j\right) \quad (2)$$

Here, V_x is

$$v_x(v, p, q, r, x) = \sqrt{(v + \frac{pr - qx}{v})^2 + (\frac{qr + px}{v})^2} \quad (3)$$

The relation of this equation (1-3) is given in following figure:

2.3 Control Model for LPC

Figure 5 shows the proposed circuit model of loop power controller by considering the branch impedance of distribution feeders and phase shifter to derive the loop power controller.

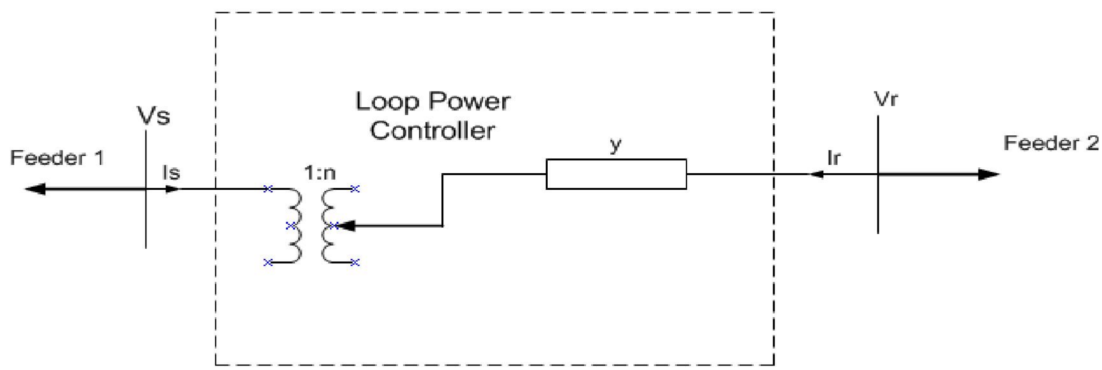

Figure 5: Circuit Model for LPC

2.4 Control Algorithm of Loop Power Flow Controller (LPC)

Figure 6 shows the working algorithm of the proposed loop power controller. To illustrate the proposed methodology, two sample radial feeders

$$P_{LPC} = \frac{P_1 - P_2}{2} \quad (4)$$

with unequal loadings are taken. The desired real and reactive power flow through the loop power

$$Q_{LPC} = \frac{Q_1 - Q_2}{2} \quad (5)$$

controller for loading balance of distribution feeders are derived as:

$$R_T = R_1 + R_2 \quad (6)$$

The total impedance of two feeders is defined as:

$$X_T = X_1 + X_2 \quad (7)$$

Where (R_1, X_1) and (R_2, X_2) are the branch impedances of the feeder 1 and feeder 2 respectively.

For the effective load transformation between the two feeders, the terminal voltage V_{L1} at the primary side of loop power control is assumed to have a fixed value of 1.0, while at the secondary side, the terminal voltage is derived as [12, 13];

$$|V_{L2}| = \sqrt{((1 + P_{LPC}R_T + Q_{LPC}X_T)^2 + (P_{LPC}X_T - Q_{LPC}R_T)^2)} \quad (8)$$

Therefore the desired phase shift and incremental voltage for optimum working of loop power controller are calculated as:

$$\Delta V = |V_{L2}| - 1.0 \quad (9)$$

$$\Delta \emptyset = tan^{-1}\left(\frac{P_{LPC}X_T - Q_{LPC}R_T}{1 + P_{LPC}R_T + Q_{LPC}X_T}\right) \quad (10)$$

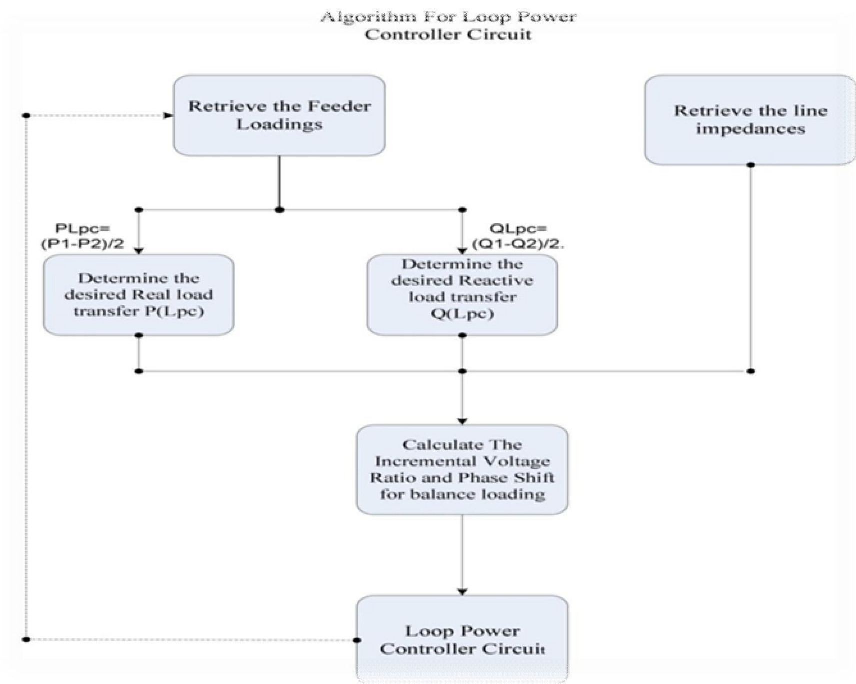

Figure 6: Algorithm Flow Chart of Loop Power Controller (LPC)

3. Case Study of Feeders of a Utility System

To demonstrate the effectiveness of the proposed LPC for loading balance, two adjacent feeders of local utility system named as feeder 1(new exchange feeder), feeder 2 (Sohny road feeder) have been selected for computer simulations [15]. The Feeder 1 is connected to Feeder 2 with an open line switch so that the load transfer can be executed for service restoration during fault emergency. Fig. 7 shows the schematic one-line diagram of the feeders connected with open tie switch. Fig. 8 shows the daily profile of real and reactive power loading of Feeders 1 and 2 without considering the any alternate power injection source. The solid blue-line shows the real power P1 and solid red-line shows the reactive power Q1 loading of Feeder 1. Similarly, the dotted blue-line shows the real power P2 and dotted red-line shows the reactive power Q2 loading of Feeder 2.

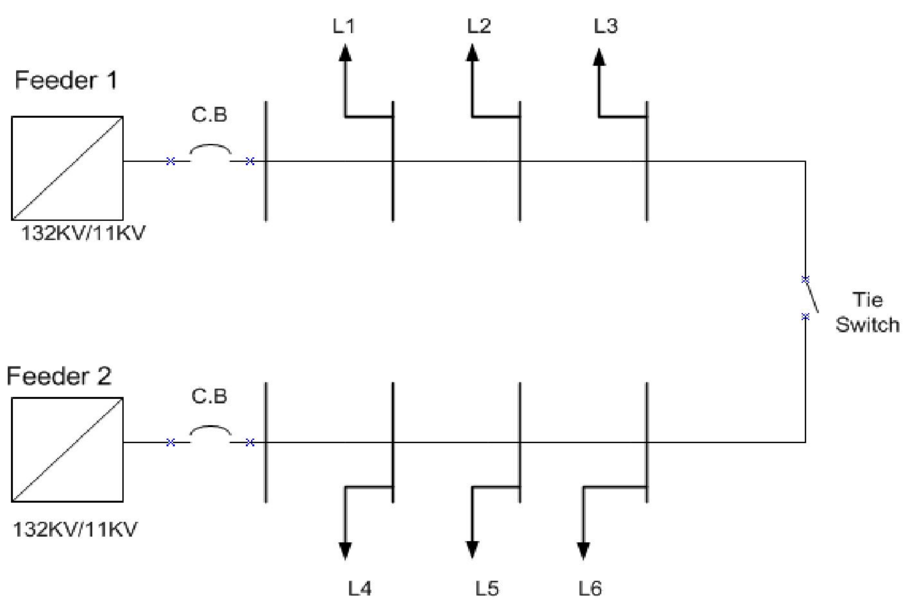

Figure 7: Schematic One line Diagram of Distribution Feeders

Table 1:- Loading Data of Feeder 1 and Feeder 2

Time	Feeder 1		Feeder 2			Feeder 1		Feeder 2	
Hour (Hr)	**P1 (KW)**	**Q1 (KVAr)**	**P2 (KW)**	**Q2 (KVAr)**	**Hour**	**P1 (KW)**	**Q1 (KVAr)**	**P2 (KW)**	**Q2 (KVAr)**
1	1457.5	0903.1	3238.9	2007.0	13	2753.1	1705.9	2105.3	1304.5
2	1457.5	0903.1	2915.0	1806.3	14	2591.1	1605.6	2105.3	1304.5
3	1376.5	0853.0	2753.1	1705.9	15	1943.4	1204.2	2267.3	1404.9
4	1295.6	0802.8	2591.1	1605.6	16	1943.4	1204.2	2429.2	1505.2
5	1295.6	0802.8	2429.2	1505.2	17	1943.4	1204.2	2429.2	1505.2
6	1457.5	0903.1	2267.3	1404.9	18	1781.4	1103.8	2267.3	1404.9
7	1457.5	0903.1	2186.3	1354.7	19	1781.4	1103.8	2267.3	1404.9
8	1619.5	1003.5	2105.3	1304.5	20	1619.5	1003.5	2429.2	1505.2
9	1943.4	1204.2	2267.3	1404.9	21	1619.5	1003.5	2591.1	1605.6
10	1943.4	1204.2	2105.3	1304.5	22	1619.5	1003.5	2915.0	1806.3
11	1943.4	1204.2	1943.4	1204.2	23	1295.6	0802.8	3077.0	1906.6
12	2105.3	1304.5	2105.3	1304.5	24	1214.6	0752.6	3400.9	2107.3

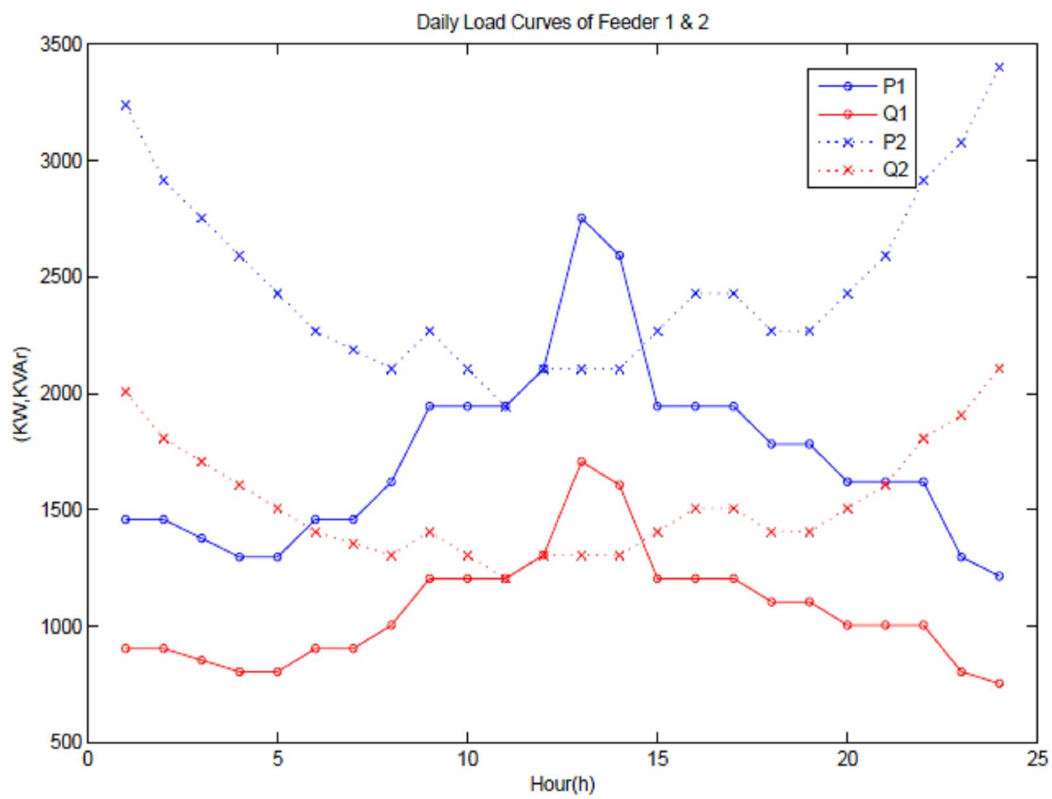

Figure 8: Active and reactive power loading of feeder1 and feeder2

3.1 Balance Loading With Loop Power Controller

With the variation of customer loading, an adaptive LPC control algorithm is derived to adjust the voltage ratio and phase shift between both feeders according to the loading intervals. To illustrate the effectiveness of LPC for system loading balance, an LPC is assumed to be installed to replace the open-tie switch between Feeders 1and 2.

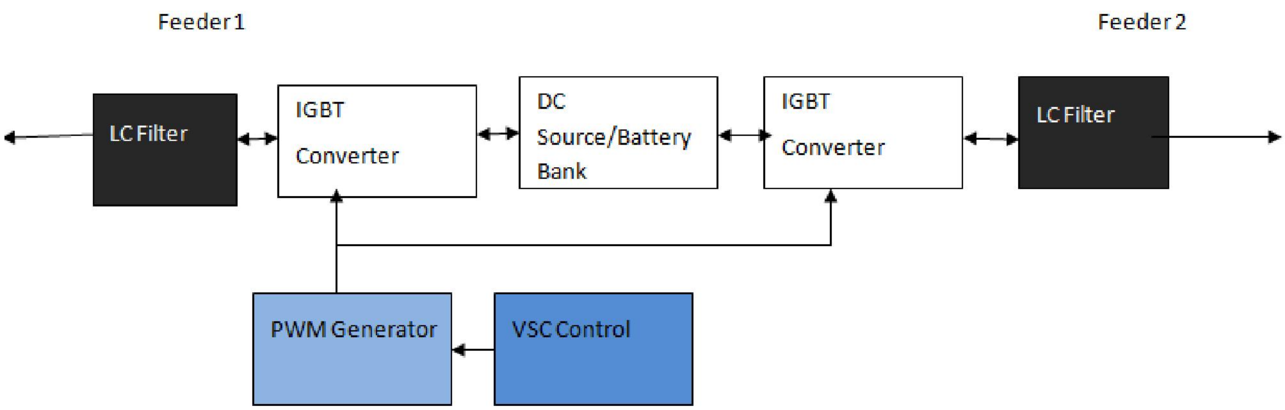

Figure 9: Block Diagram of Loop Power Controller

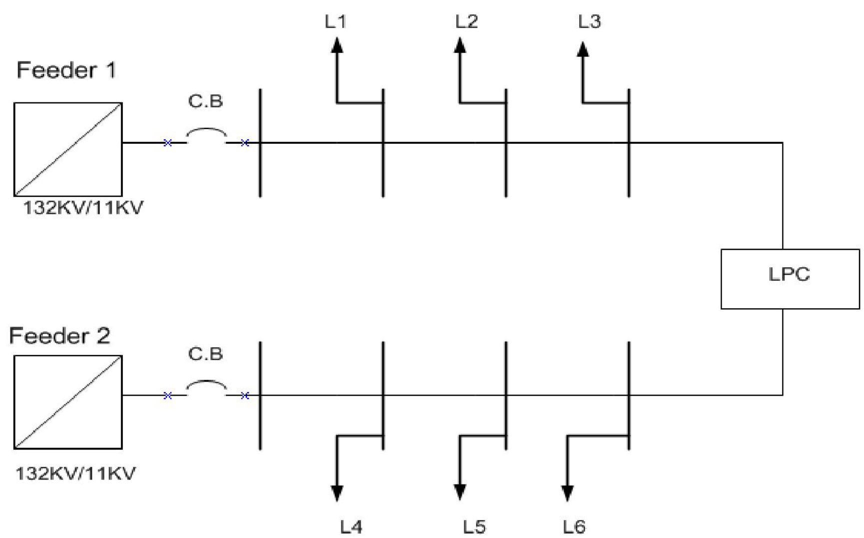

Figure 10: Schematic One line Diagram Distribution feeders with LPC

Table 2: The required bidirectional transfer values of active and reactive power between adjacent feeders

Hour	**P**Lpc (KW)	**Q**Lpc (KVAr)	**Hour**	**P**Lpc (KW)	**Q**Lpc (KVAr)
1	-890.7	-551.95	13	323.9	200.7
2	-728.75	-451.6	14	242.9	150.55
3	-688.3	-426.45	15	-161.95	-100.35
4	-647.75	-401.4	16	-242.9	-150.5
5	-566.8	-351.2	17	-242.9	-150.5
6	-404.9	-250.9	18	-242.95	-150.55
7	-364.4	-225.8	19	-242.95	-150.55
8	-242.9	-150.5	20	-404.85	-250.85
9	-161.95	-100.35	21	-485.8	-301.05
10	-80.95	-50.15	22	-647.75	-401.4
11	0	0	23	-890.7	-551.9
12	0	0	24	-1093.15	-677.35

Table 3: The corresponding voltage ratio and phase shift for each study hour (Loop Power Control Parameters)

LPC Control Parameters					
Hour	ΔV(P.u)	Phase angel (Φ)	Hour	ΔV(P.u)	Phase angel (Φ)
1	-0.187081	-11.934	13	0.653956	-2.11745
2	-0.511306	-16.3471	14	0.490391	-1.76398
3	-0.591652	-18.5352	15	-0.325719	2.59727
4	-0.670801	-21.7997	16	-0.011	-0.40
5	-0.821924	-36.9052	17	-0.487488	5.12887
6	-0.800856	22.5614	18	-0.487639	5.13407
7	-0.725703	14.5172	19	-0.487639	5.13407
8	-0.487488	5.12887	20	-0.800726	22.5356
9	-0.325719	2.59727	21	-0.905946	77.2085
10	-0.16299	1.04474	22	-0.670801	-21.7997
11	0	0	23	-0.187233	-11.9319
12	0	0	24	0.220808	-9.72608

Fig 9 shows the block diagram of developed loop power controller and Fig 10 shows the deployment of loop power controller to replace the open tie switch in adjacent feeders. Table 2 shows the required bidirectional transfer values of active and reactive power between adjacent feeders. Table 3 shows the corresponding voltage ratio and phase shift for each study hour, which are derived from (9) and (10) for LPC control to achieve the load transfer between both feeders.

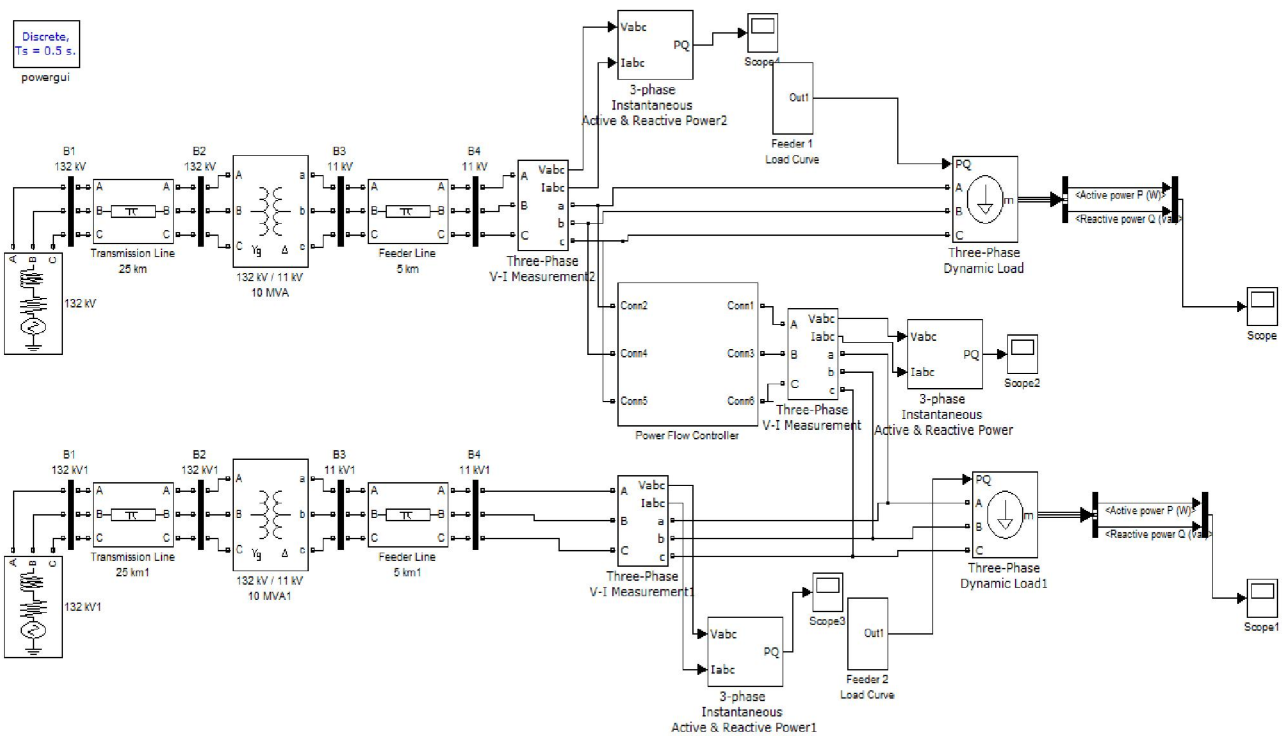

Figure 11: Simulation Circuit of Distribution Feeders

Figure 11 shows the simulation circuit of tested feeders with LPC strategy. Moreover the figure 12 shows the working strategy of loop power controller based on PWM control according to derived parameters. Figure 13 shows the optimum loading obtained after the application of loop power controller on the study feeders. The derived parameters (change in voltage, Phase shift) are the control parameters for the optimum working of the loop power controller (LPC). The figure 14 and 15 shows the derived control parameters of given load curve for the effective operation of loop power controller.

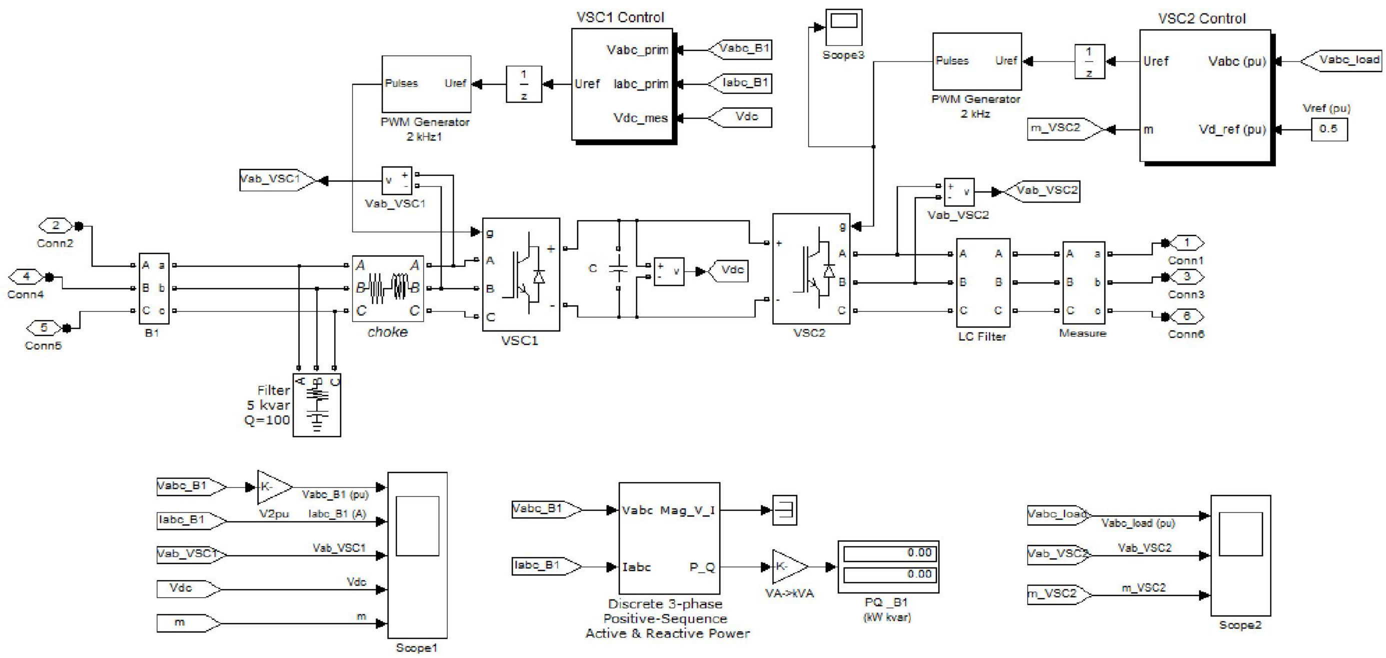

Figure 12: Simulation Diagram of Loop Power Controller

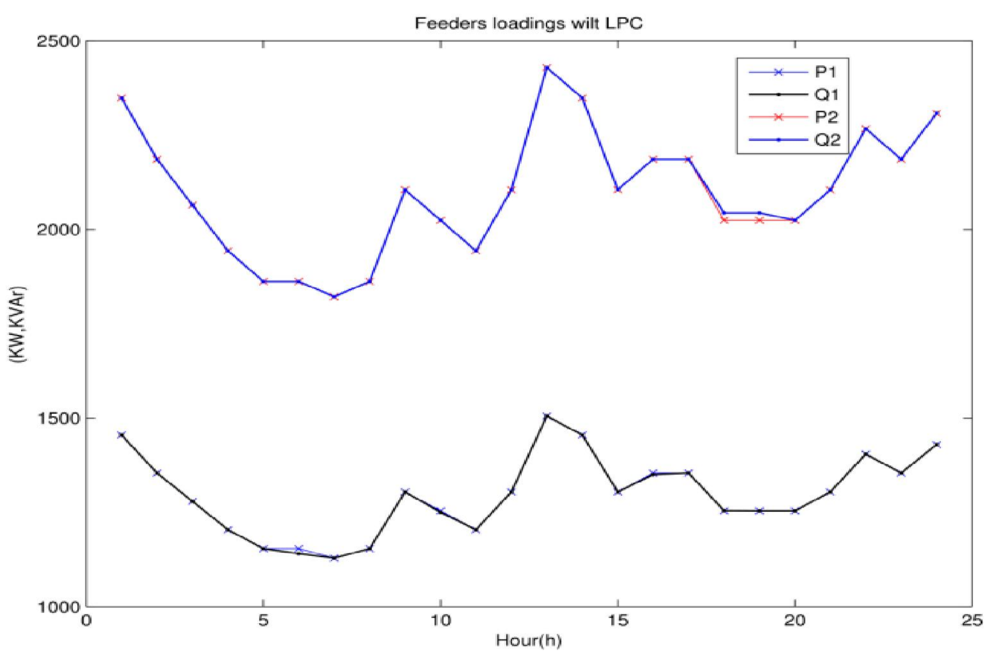

Figure 13: Power Profiles with LPC

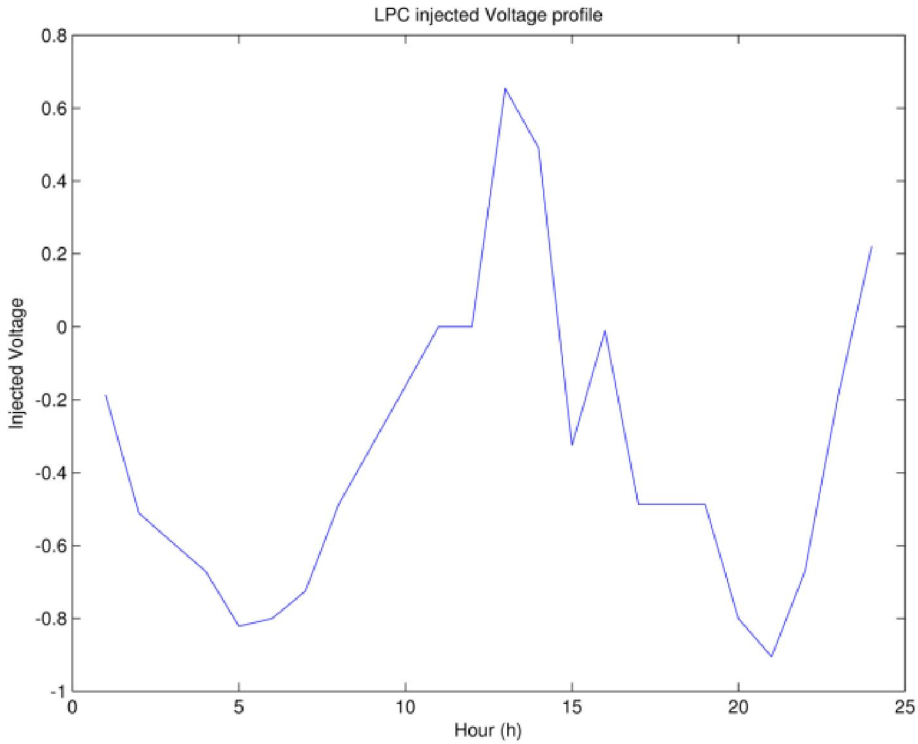

Figure 14: Injected Voltage (P.U) by LPC

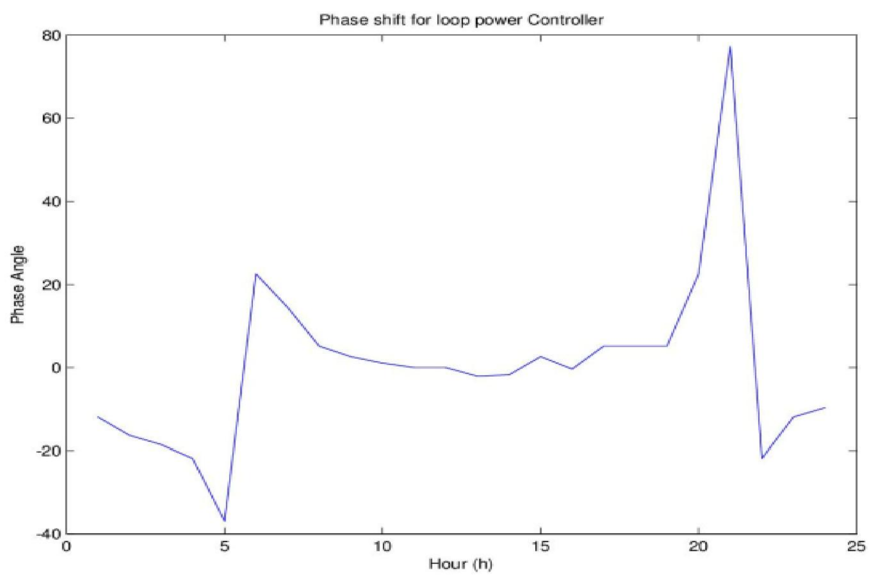

Figure 15: Desired Phase Shift

4. Discussion

Balance loading on distribution feeders is vital for the effective operation of distribution networks. In this paper we developed and implemented a PWM-IGBT inverter based innovative loop power flow control strategy whose results give us a balanced and smooth load curve of distribution feeders. One day load curve of two adjacent feeders of local utility system has taken for the computer simulation of proposed strategy. Work in [5, 6, 7, 8, 10] provides a wide range of control strategies developed on the analogy of FACTS devices for optimal power flow control but the work in this paper gives reliable, efficient and effective operation in terms of rapid switching rate and minimized losses.

Conclusion

This study evaluates a back-to-back converter with sinusoidal pulse width modulation PWM control based LPC that replaces the open tie switch for the control of real and reactive power transfer between distribution feeders to achieve balance loading on distribution networks. According to mismatches of real and reactive power loadings between the feeders for each study hour, the corresponding voltage ratio and phase shift adjusted by the loop power controller are derived. By applying the control algorithm of LPC to adjust the voltage ratio and phase shift between both feeders, the proper amount of real power and reactive power can be transferred from the heavily loaded feeder to the lightly loaded feeder for each study hour. According to the simulation results, it is concluded that the loading balance of distribution systems with fluctuating load can be obtained effectively by the implementation of LPC to achieve adaptive control of load transfer between distribution feeders. Moreover the power loss reduction of test feeders after balance loading by LPC can also be derived.

References:

1. T. Ishikawa and Y. Imai, “Outline of Islanding Detection Technology”, T. IEE Japan, Vol.116-B, No.5, pp.521-524 (1996).
2. H. Taniguchi, “Dispersed Generation and Power System Control”, T. IEE Japan, Vol.121-B, No.9, pp.1065-1068 (2009).
3. J. Kim, H. Kita, T. Tezuka, and Y. Nishikawa, “Method of Determining the Introduction Limits of Dispersed Generation System in Distribution System from a Viewpoints of Voltage Regulation”, T. IEE Japan, Vol. 116-B, No. 12, pp. 1461-1469.
4. N. Okada and T. Ishikawa, “The distinctive feature of the grid connected PV systems”, The Papers of Technical Meeting on Frontier Technology and Engineering, IEEE Japan, FTE-00-6, pp. 37-42 (2003)
5. N. Okada, Autonomous Loop Power Flow Control for Distribution System 7th lnternational Conference on AC and DC Power Transmission, IEE, No. 485, 2001, pp 150- I55.
6. N. Okada, “Basic study on installation and control method for loop power flow controller in distribution system”, the 14th Conference of the Electric Power Supply Indushy, 2002.
7. Hayakawa, N., *et al.,* “Feasibility Study of Superconducting Power Flow Controller and Fault Current Limiter (SPFCL)”IEEE transactions on Super Conductivity, Vol.23, Issue 3, Jun.2013.
8. S.Sreejith, *et al.,* “Optimal location of interline power flow controller in a power system network using ABC algorithm” Archives of Electrical Engineering, Volume 62, Issue 1, Pages 91–110,March.2013.
9. Lokman H. Hassan, *et al.,* “Application of genetic algorithm in optimization of unified power flow controller parameters and its location in the power system network” International Journal of Electrical Power & Energy Systems, Volume 46, March 2013, Pages 89–97.
10. R. Pillay Carpanen, *et al.,* “An improved SSSC-based power flow controller design method and its impact on torsional interaction” International Journal of Electrical Power & Energy Systems, Volume 43, Issue 1, December 2012, PP 194–209
11. Chauo-Shen Chen, *et al.,* “Loading Balance of Distribution Feeders with Loop Power Controllers Considering Photovoltaic Generation” IEEE transactions on Power System, Vol.26, Issue 3.Aug 2011.
12. Y. Zhu and K. Tomsovic, “Adaptive power flow method for distribution systems with dispersed generation,”IEEE Trans. Power Del., vol. 17,no. 3, pp. 822–827, Jul. 2002.
13. N. Okada, “Verification of control method for a loop distribution system using loop power flow controller,” inProc. 2006 IEEE PES Power Syst. Conf. Expo., Atlanta, GA, Oct./Nov. 2006, pp. 2116–2123.
14. H. Taniguchi, “Dispersed Generation and Power System Control”, T. IEE Japan, Vol.121-B, No.9, pp.1065-1068 (2009).
15. Mahmood.T, PhD dissertation, “State estimation technique for impedance matching in distribution feeder reconfiguration” Jun.2009.

11/12/2013