International Journal of Science Engineering and Advance Technology

A Novel Control Strategy of PV Generation System with LPC for Loading Balance of Distribution Feeders

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***Abstract:*— To reduce the power loss and power flow over loading in a distribution system. Proper loading balance of distribution feeders is important. In this paper, a loop power controller (LPC) is applied for the control of real power and reactive power flows by adjusting voltage ratio and phase shift so that the loading balance of distribution feeders can be obtained. And also photovoltaic (PV) power generation is incorporated in balancing the feeder loading. For achieving the proper loading balance and load transfer line impedance of distribution feeders are used to derive the voltage ratio and phase shift of the LPC. Matlab simulations indicated that loading balance can be achieved in distribution feeders with large PV system installation by using loop power controllers according to the variation of solar energy and power loading of study feeders. By using LPC proper loading of feeders is being achieved and the power loss is being reduced as simulated in this paper.**

I. INTRODUCTION

As per the increasing demand in power and advancements in power electronics most distribution generations like solar and wind energy are being interconnected to the power system planning and operation to achieve co_2 to reduce consumption of fossil fuels by conventional thermal power generation. Penetration of wind power generation and PV power generation into distribution systems is expected to increase dramatically, which raises concerns about system impact by the intermittent power generation of DG [1]–[3]. Compared to large-scale wind power and conventional bulk generation, the generation cost of a PV system is relatively higher generally in summer peak periods it is difficult to maintain the loading balance of main transformer and the feeders due to the usage of air conditioners. Loading balance is also important for both schedule outages and service restoration after fault isolation to perform load transfer between distribution feeders to achieve better distribution system planning, loading balance is designed by the optimal reconfiguration of distribution networks so that system load demand can be evenly allocated among feeders and main transformers in substations. For distribution system operation, the loading balance is obtained by changing the open/closed status of line switches along distribution feeders so that partial loading of heavily loaded feeders/transformers can be transferred to relatively lightly loaded feeders/transformers with the adjustment of service zones. However, feeder loading varies from time to time, which will make it very difficult to obtain the desired load balance with the network configuration in the system planning stage. Further, with more and more renewable distributed generation such as wind power and PV power being installed in distribution feeders, loading balance of distribution systems becomes more of a challenge due to the injection of intermittent power generation. Applying power electronics based flexible AC transmission system (FACTS) has been proven highly effective for controlling the load transfer between feeders to achieve loading balance [5].

PV system with large capacity, the feeder loading will be varied dramatically because the power injection by PV generation is varied with the intensity of solar radiation. The load transfer between feeders with an open-tie switch must be adaptively adjusted according to PV power generation. Due to the intermittent power generation by PV systems, it becomes very difficult to achieve loading balance with conventional network reconfiguration methods by changing the status of line switches. With the advancement of power electronics, the back-to-back (BTB) converters can be applied to replace the open-tie switch for better control of real power and reactive power load transfer by changing the voltage ratio and phase shift between two feeders according to the power unbalance at any time instant [11].

For the distribution system with high penetration of renewable energy sources, voltage profiles and loading balance have to be enhanced by improving the power exchange capability between feeders. This study proposes a loop power controller (LPC) [12], [13] to replace the conventional open-tie switch so that loading balance of distribution feeders can be obtained by power flow control in a more active manner. A transformer less converter with snubber less insulated gate bipolar transistor (IGBT) is applied to the proposed LPC using an active-gate-control (AGC) scheme. The AGC scheme can balance the collector voltage of IGBTs connected in series and allow the converter to connect directly to distribution feeders with a high enough AC voltage output [14]. Additionally, LPC can reduce the voltage fluctuation and system power loss by enhancing reactive power compensation. In this paper, the three-phase balanced flow condition is assumed for both distribution feeders to perform the load transfer by LPC.

II. LPC DISTRIBUTION AUTOMATION SYSTEM

To enhance reliability and operation efficiency of distribution systems, the fully integrated distribution automation system (DAS) in Fig. 1 has been implemented by Taiwan Power Company (Taipower). The DAS consists of a master station (MS) with application software, remote terminal units (RTUs) in the substations, feeder terminal units (FTUs), and automatic line switches along the primary feeders [15]. The distribution feeders from substations are connected as the open loop configuration with one of the automatic line switches being selected as the open-tie switch.

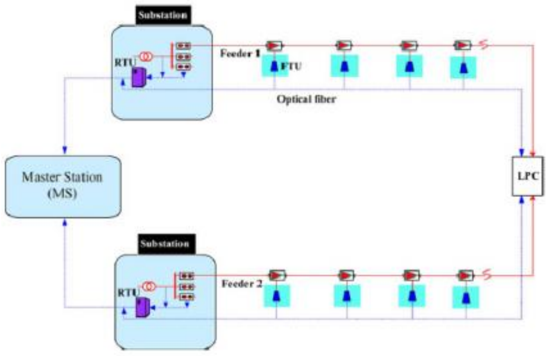

Fig. 1. Distribution automation system with a loop power controller.

To achieve loading balance of distribution feeders for normal operation with variation of feeder loading, the non-interruptible load transfer is executed by closing the open-tie switch and opening one of the normal close switches. When a fault contingency occurs, the feeder circuit breaker trips, and the over-current fault flags of all upstream FTUs are set due to the large fault current flows. After the MS retrieves all fault flags, the fault location can therefore be determined according to the combination of fault flags and the network topology. The MS then sends the command to open all line switches around the faulted section to complete the fault isolation and followed by reclosing the feeder circuit breaker to restore power service to upstream customers. After verifying the reserve capacity of the supporting feeder, the open-tie switch is closed to fulfill the service restoration of downstream customers [16]. Although the DAS has been applied for fault restoration effectively in Taipower, the loading balance is difficult to be performed for distribution system with large DG facility because too frequently the switching operation is required to accommodate the dramatic fluctuation of DG generation.

To solve the problem, Fig. 1 shows how the proposed LPC is applied to replace the open-tie switch by achieving adaptive power flow control for load transfer. The distribution feeder-pair with LPC provides the following advantages: 1) improved controllability and operational flexibility of the distribution system; 2) mitigation of voltage fluctuation with fast reactive power compensation; 3) control of the real and reactive power flow; 4) reduced power system loss with improved loading balance of the distribution system; and 5) enhanced system robustness for integration with more renewable energy [11].

III. CONTROL MODEL OF LOOP POWER CONTROLLER

Loop power controller is proposed in the circuit model considering the branch impedances of distribution feeders for the simulation of feeder loading balance. Fig. 2 shows the overall process to derive the LPC control algorithm to enhance loading balance of distribution feeders

A. Simulation of Feeder Loading Balance

In this study, the LPC is considered as the combination of tap changer and phase shifter with a circuit model as shown in Fig. 3. By adjusting the voltage ratio and phase shift between both sides of the LPC according to the branch impedance and loading unbalance of distribution feeders, the real and reactive power flows through the LPC can be controlled to achieve the loading balance. The equivalent circuit model can be represented as an ideal transformer with turn ratio of $1 : n^{j\ \varnothing}$ and a series admittance y.

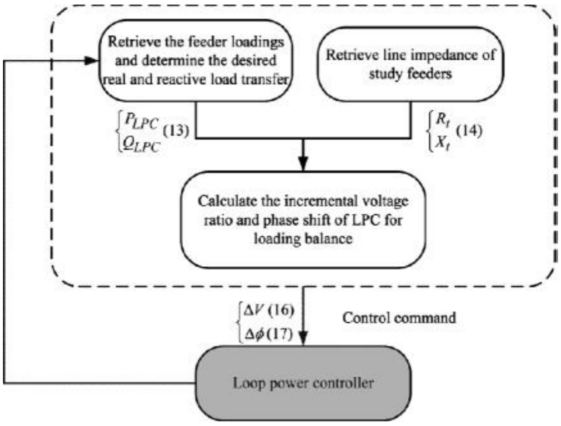

Fig. 2. Flowchart of LPC control algorithm

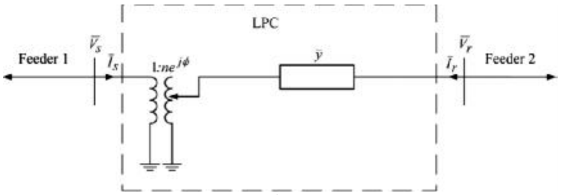

Fig. 3. Circuit model of loop power controller.

The mathematical model of LPC can be illustrated in (1) to represent the relationship between the node injection currents and voltages:

$$\begin{bmatrix}\bar{i_s}\\ \bar{i_r}\end{bmatrix}=\begin{bmatrix}n^2\bar{y} & -n^2\bar{y}\\ -\bar{n}\bar{y} & \bar{y}\end{bmatrix}\begin{bmatrix}\bar{v}_s\\ \bar{v}_r\end{bmatrix} \qquad (1)$$

Where $\bar{n}=ne^{j\varphi}$

To simplify the process to determine the voltage ratio and phase shift of LPC, this paper proposes a modified equivalent circuit with dependent currents source $d\bar{i}_s$ and $d\bar{i}_r$ as shown in Fig. 4. Here, the dependent current sources are revised according to the adjustments of turn ratio and phase shift during the iteration process. To derive the injection currents due to the change of voltage ratio by LPC, the node currents are represented by assuming zero phase shift as follows:

$$i_s=n^2\bar{y}\bar{v}_s\text{-n}\bar{y}\bar{v}_r$$
$$=(n^2-1)\overline{\bar{y}\bar{v}_s}+(1-n)\bar{y}\bar{v}_r+\bar{y}(\bar{v}_s-\bar{v}_r) \qquad (2)$$
$$.i_r=-n\bar{y}\bar{v}_s+\bar{y}\bar{v}_r$$
$$=(1-n)\bar{y}\bar{v}_s+\bar{y}(\bar{v}_r-\bar{v}_s) \qquad (3)$$

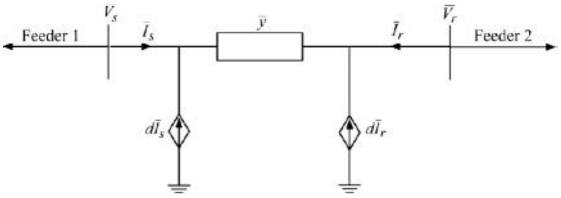

Fig. 4. Modified equivalent circuit model of LPC.

The equivalent injection currents are solved as

$$di_{s'}=-(n^2-1)\bar{y}\bar{v}_s-(1-n)\bar{y}\bar{v}_r \qquad (4)$$
$$di_{r'}=-(1-n)\bar{y}\bar{v}_s \qquad (5)$$

To derive the injection current due to the change of phase shift by LPC, the node currents are represented by assuming a fixed voltage ratio of 1.0 as follows:

$$i_s=\bar{y}\bar{v}_s-\bar{y}\,e^{-j\varphi}\bar{v}_r$$
$$=(1-e^{-j\varphi})\bar{y}\bar{v}_r+\bar{y}(\bar{v}_s-\bar{v}_r) \qquad (6)$$
$$i_r=(1-e^{-j\varphi})\bar{y}\bar{v}_s+\bar{y}(\bar{v}_r-\bar{v}_s) \qquad (7)$$

The equivalent injection currents are solved as

$$di_{s''}=-(1-e^{-j\varphi})\bar{y}\bar{v}_r \qquad (8)$$

$$di_{r''}=-(1-e^{-j\varphi})\bar{y}\bar{v}_s \qquad (9)$$

Therefore, the equivalent currents due to the change of both voltage ratio and phase shift by LPC in Fig. 4 are determined as follows:

$$di_s=di_{s'}+di_{s''} \qquad (10)$$
$$di_r=di_{r'}+di_{r''} \qquad (11)$$
$$\begin{bmatrix}d\bar{i_s}\\ d\bar{i_r}\end{bmatrix}=\begin{bmatrix}(1-n^2)\bar{y} & (n+e^{-j\varphi}-2)y\\ (n-1)\bar{y} & (n+e^{j\varphi}-2)\bar{y}\end{bmatrix}\begin{bmatrix}\bar{v}_s\\ \bar{v}_r\end{bmatrix} \qquad (12)$$

By this way, the network impedance matrix remains unchanged during the iteration process to solve the voltage ration and phase shift of LPC.

B. LPC Control Algorithm

Two radial feeders connected with an LPC is presented in a Fig. 5. control algorithm for LPC to achieve feeder loading balance is proposed. The desired real and reactive power flows through the LPC for feeder loading balance are defined as

$$p_{lpc}=\frac{p_1-p_2}{2}$$
$$q_{lpc}=\frac{q_1-q_2}{2} \qquad (13)$$

If the branch impedances of Feeder 1 and Feeder 2 are $(R_{1,},X_1)$ and $(R_{2,},X_2)$ respectively, the total impedance oftwo feeders is defined as

$$\begin{cases}R_T=R_1+R_2\\ X_T=X_1+X_2\end{cases} \qquad (14)$$

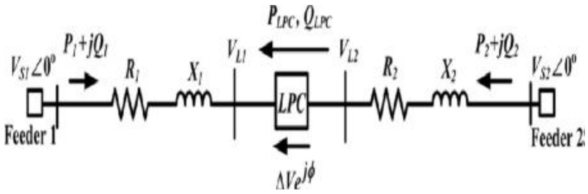

Fig.5. Incremental circuit model of distribution feeders with LPC.

In order to perform the LPC control strategy to have the proper load transfer between both feeders for loading balance, the terminal voltage v_{l1} at the primary side of LPC is assumed to have a fixed value of 1.0 The terminal voltage at the secondary side of LPC is derived in (15):

$$|v'_{l2}| = \sqrt{(1 + P_{LPC}R_T + Q_{LPC}X_T)^2 + (P_{LPC}X_T + Q_{LPC}R_T)^2} \quad (15)$$

The incremental terminal voltage ΔV and phase shift $\Delta\varphi$ are therefore calculated as follows

$$\Delta v = |v'_{12}| - 1.0 \quad (16)$$

$$\Delta\varphi = \tan^{-1}\frac{p_{lpc}x_t - q_{lpc}r_t}{1 + p_{lpc}r_t + q_{lpc}x_t} \quad (17)$$

IV. RESULTS AND DISCUSSION

To demonstrate the effectiveness of the proposed LPC for loading balance of distribution feeders with PV facility is being considered and the MATLAB circuit consisting of two feeders suplying local loads interconnected by LPC. Each feeder is saperately connected from the generating end.

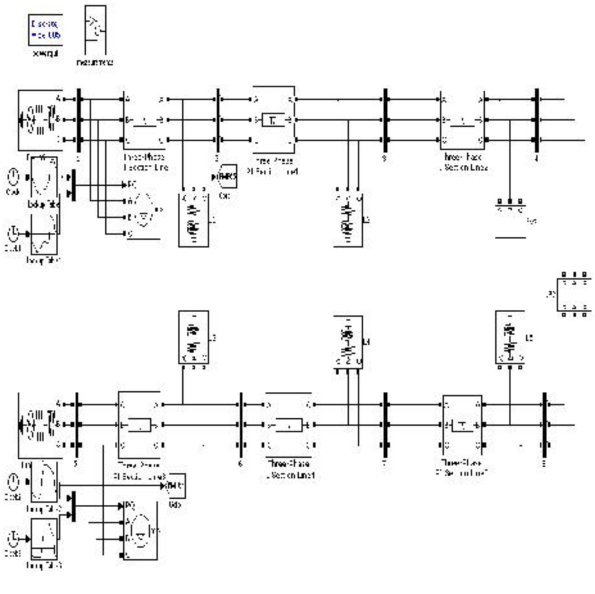

Fig. 6 MATLAB circuit of feeders interconnection with LPC

Feeders loading balance with PV and without PV system is being simulated .and then to obtain the optimal loading between the feeders LPC is placed between two feeders in the place of open tie switch and system is being simulated.

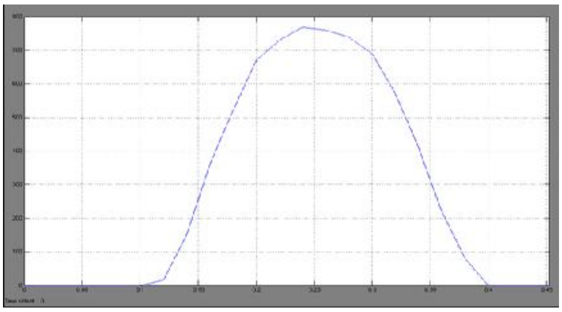

Fig. 7. Power generation of a PV system

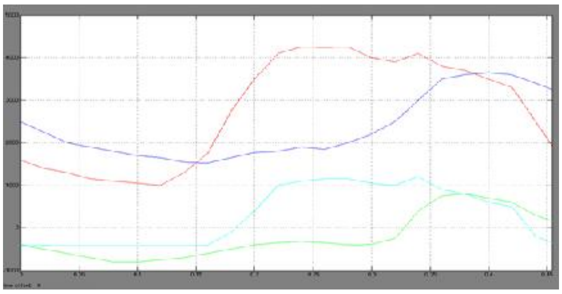

Fig. 8. Power profiles of Feeder F1 and F2 (without PV system)

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Fig. 8 shows the daily profiles of real and reactive power loading of Feeders F1 and F2 without considering the power injection by the PV system.

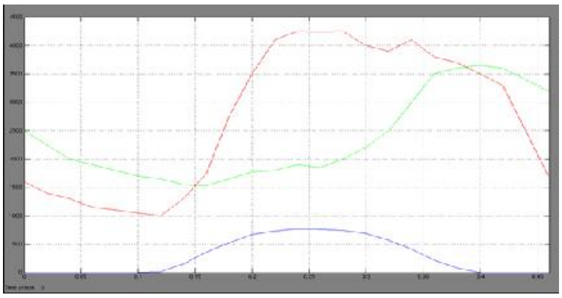

Fig. 9. Power profiles of Feeder MF65 and MU67 (with PV system).

Fig. 9 shows the reduction of real power loading of Feeder F1 during daytime period after integrating PV power generation in the distribution system.

A. Loading Balance of Distribution Feeder by a Loop Power Controller

With the variation of customer loading profiles and the intermittent generation of PV systems, an adaptive LPC control algorithm is derived to adjust the voltage ratio and phase shift between both feeders according to the feeder loading and PV generation. 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 F1 and F2

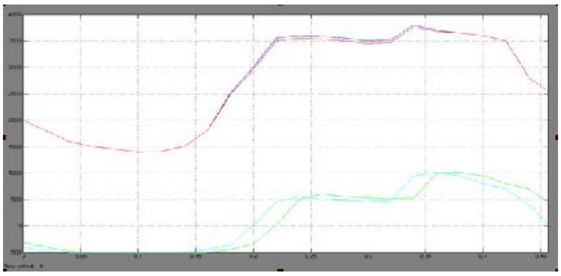

Fig. 10. Loading balance of both feeders with the control of LPC (w/o PV system).

Figure 10 shows the execution of loading balance by LPC for the distribution system without considering the PV system Fig. 11 shows the real power and reactive power profiles of both feeders. By comparing to Fig. 9, it is found that the loading balance of the study system is significantly improved by LPC.

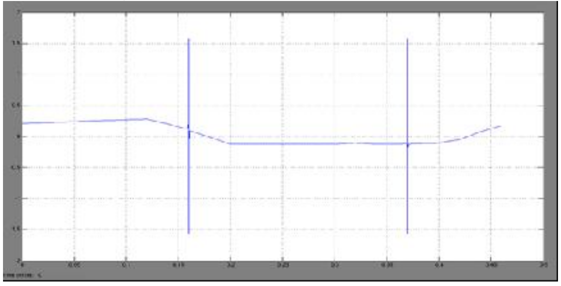

Fig 11(a) voltage ratio

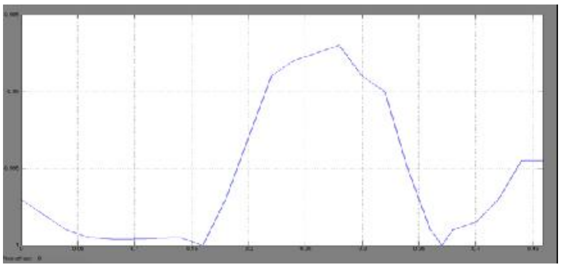

Fig11(b) phase shift

Fig. 11(a). (b) Shows voltage ratio and phase shift for the power transfer by LPC (without the PV system).

Fig. 11 shows the corresponding voltage ratio and phase shift, LPC control to achieve the load transfer between both feeders.

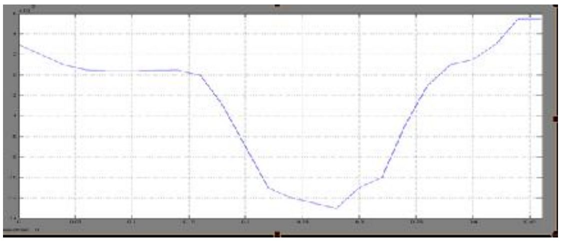

Fig. 12(a)

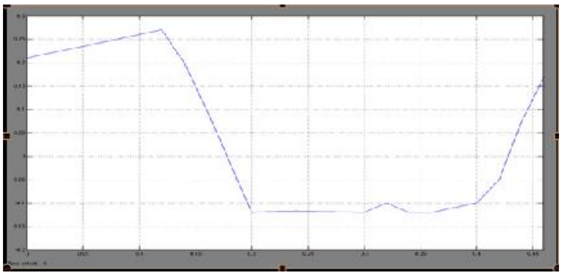

Fig. 12.(b) Voltage ratio and phase shift with the control of LPC (with PV system).

When the PV system is integrated in the distribution system, the power loading of Feeder F1 is reduced as PV power generation is injected into the system during the daytime period. To achieve the loading balance, the voltage ratio and phase shift by LPC have to be revised as shown in Fig. 12 according to the variation of PV power generation. By comparing to Fig. 11, the voltage ratio of LPC remains the same because the PV system does not generate reactive power. However, the phase shift of LPC required for real power balancing is increased during the daytime period when the real power generated by the PV system is injected. For instance, a larger phase shift of is applied for real power transfer .With the control of LPC, the loading balance of test feeders by including the PV power generation has been obtained as shown in Fig. 13

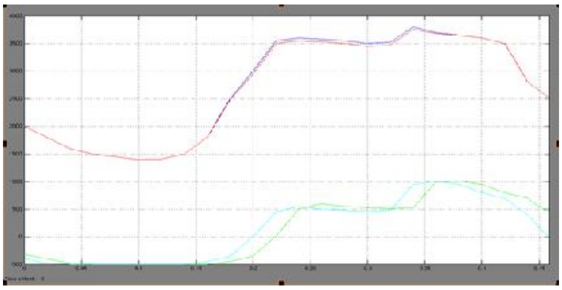

Fig. 13. Loading balance of both feeders with the control of LPC (with PV system).

B. Distribution Feeder Loss Analysis

To investigate the effectiveness of LPC for the reduction of system power loss by loading balance, a three-phase power flow analysis is performed for both feeders F1 and F2 by considering the feeder power loading profiles before and after loading balance. Also, the loss incurred in LPC is assumed to be 1% of the power transfer by the LPC which has been included in the system loss.

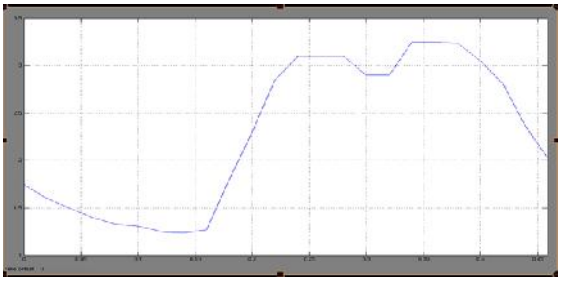

Fig 14(a)

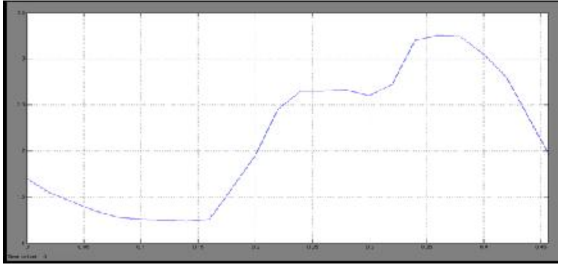

FIG 14 (b)

Fig. 14. Percentage of system power loss before and after applying LPC for loading balance (with PV system).

The system power loss reduction has therefore been obtained after implementing the LPC for loading balance.

V. CONCLUSIONS

In this paper efforts are made to reduce the distribution system feeder over loading and system power loss by using. 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 loading feeder to the lightly loading feeder. According to the computer simulation, it is concluded that the loading balance of distribution systems with intermittent PV power generation can be obtained effectively by the implementation of LPC. By balancing the load between the two test feeders .power loss in the feeders is being reduced as simulated in this paper

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