

LOADING BALANCE OF DISTRIBUTION FEEDERS WITH LOOP POWER CONTROLLERS CONSIDERING FUEL CELL GENERATION

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ABSTRACT- For the operation of distribution systems, loading balance of distribution feeders is important for reducing power loss and mitigating power flow overloading. 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. To incorporate fuel cell power generation in feeder loading balance, a distribution feeder with large fuel cell installation is selected for computer simulation. Daily loading unbalance is determined by analyzing fuel cell power generation recorded by the SCADA system and by constructing daily power load profiles based on distribution automation system (DAS) data. The load transfer required to achieve loading balance and the line impedance of distribution feeders are used to derive the voltage ratio and phase shift of the LPC. Computer simulations indicated that loading balance can be achieved in distribution feeders with large fuel cell system installation by using loop power controllers. The system power loss reduction resulting from feeder loading balance by LPC is also investigated in this paper.

Index Terms— Distribution automation system, loop power controller, fuel cell.

I. INTRODUCTION

Environmental-friendly distributed generation systems (DGS) such as fuel cells, wind turbines, hydro turbines or photovoltaic arrays are rapidly increasing around the world because they can meet both the increasing demand of electric power and environmental regulations due to green house gas emission. Outstanding advances in Power Electronics and energy storage devices for transient backup have accelerated penetration of the DGS into electric power generation plants.

These DGS technologies can be used for various applications to a standalone, a grid interconnection, a cogeneration, a standby, peak shavings, etc. and have many benefits such as

environmental-friendly, modular electric generation, increased reliability, high power quality, uninterruptible power service, cost savings, on-site generation, and expandability, etc.

A fuel cell is an electrochemical cell that converts a source fuel into an electrical current. It generates electricity inside a cell through reactions between a fuel and an oxidant, triggered in the presence of an electrolyte. The reactants flow into the cell, and the reaction products flow out of it, while the electrolyte remains within it. Fuel cells can operate continuously as long as the necessary reactant and oxidant flows are maintained. Fuel cells are different from conventional electrochemical cell batteries in that they consume reactant from an external source, which must be replenished^[1] – a thermodynamically open system. By contrast, batteries store electrical energy chemically and hence represent a thermodynamically closed system.

Many combinations of fuels and oxidants are possible. A hydrogen fuel cell uses hydrogen as its fuel and oxygen (usually from air) as its oxidant. Other fuels include hydrocarbons and alcohols. Other oxidants include chlorine and chlorine dioxide. Fuel cells come in many varieties; however, they all work in the same general manner. They are made up of three segments which are sandwiched together: the anode, the electrolyte, and the cathode. Two chemical reactions occur at the interfaces of the three different segments. The net result of the two reactions is that fuel is consumed, water or carbon dioxide is created, and an electrical current is created, which can be used to power electrical devices, normally referred to as the load.

At the anode a catalyst oxidizes the fuel, usually hydrogen, turning the fuel into a positively charged ion and a negatively charged electron. The electrolyte is a substance specifically designed so ions can pass through it, but the electrons cannot. The freed electrons travel through a wire creating the electrical current. The ions travel through the electrolyte to the cathode. Once reaching the cathode,

the ions are reunited with the electrons and the two react with a third chemical, usually oxygen, to create water or carbon dioxide.

DESIGN FEATURES IN A FUEL CELL ARE:

- The electrolyte substance. The electrolyte substance usually defines the type of fuel cell.
- The fuel that is used. The most common fuel is hydrogen.
- The anode catalyst, which breaks down the fuel into electrons and ions. The anode catalyst is usually made up of very fine platinum powder.
- The cathode catalyst, which turns the ions into the waste chemicals like water or carbon dioxide. The cathode catalyst is often made up of nickel.

A typical fuel cell produces a voltage from 0.6 V to 0.7 V at full rated load. Voltage decreases as current increases, due to several factors:

- Activation loss
- Ohmic loss (voltage drop due to resistance of the cell components and interconnects)
- Mass transport loss (depletion of reactants at catalyst sites under high loads, causing rapid loss of voltage).

To deliver the desired amount of energy, the fuel cells can be combined in series and parallel circuits, where series yields higher voltage, and parallel allows a higher current to be supplied. Such a design is called a fuel cell stack. The cell surface area can be increased, to allow stronger current from each cell.

It is critical for distribution systems to achieve loading balance of main transformers and feeders to prevent the system overloading problem during the summer peak period 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, PV power and fuel cell 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].

Considerable efforts have been proposed in the previous works to solve the loading balance of distribution systems. The distribution static compensator (DSTATCOM) was considered for compensation of loading unbalance caused by stochastic load demand in distribution systems [6]. The control algorithm for static var compensation (SVC) has been developed for loading balance at any given power factor [7]. Fuzzy multi objective and Tabu search have been used to optimize the on/off patterns of tie switches and sectionalizing switches to achieve feeder loading balance in distribution systems with distributed generators [8]. A heuristic-expert system approach for network reconfiguration to enhance current balance among distribution feeders was presented by Reddy and Sydulu [9]. A Petri-Net algorithm has also been proposed for loading balance of distribution systems with open loop configuration by identifying open-tie switches [10].

For the distribution system with large capacity of fuel cell installation, the feeder loading will be varied dramatically because the power injection by fuel cell generation. The load transfer between feeders with an open-tie switch must be adaptively adjusted according to fuel cell power generation. Due to the intermittent power generation by fuel cell 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 transformerless converter with snubberless 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.

The design of the LPC control strategy must consider intermittent power injection by fuel cell power generation and varying feeder loading so that the loading unbalance and system power loss can be minimized in each study hour. This paper is organized as follows. First, Section II introduces the distribution automation system with a loop power controller. Section III presents the feeder loading balance simulation and LPC control algorithm. In Section IV, the impact of the fuel cell system on feeder loading balance and loss reduction of the distribution system is investigated. Finally, Section V gives conclusions.

II. DISTRIBUTION AUTOMATION SYSTEM WITH LOOP POWER CONTROLLER

To enhance reliability and operation efficiency of distribution systems, the fully integrated distribution automation system (DAS) in Fig. 1 is implemented. 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. To achieve loading balance of distribution feeders for normal

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

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].

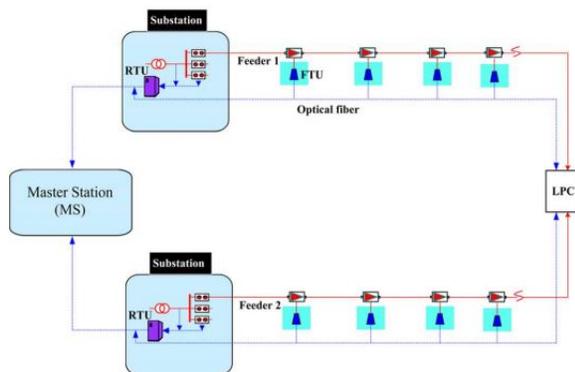
Although the DAS has been applied for fault restoration effectively, the loading balance is difficult to be performed for distribution system with large DG facility because too frequently the switching operation is required to accommodate the dramatic fluctuation of DG generation. To solve the problem, 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].

II. CONTROL MODEL OF LOOP POWER CONTROLLER

To derive the voltage ratio and phase shift of LPC for the control of load transfer, the equivalent circuit model of LPC is proposed by 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 $1:n e^{j\varphi}$ and a series admittance y .

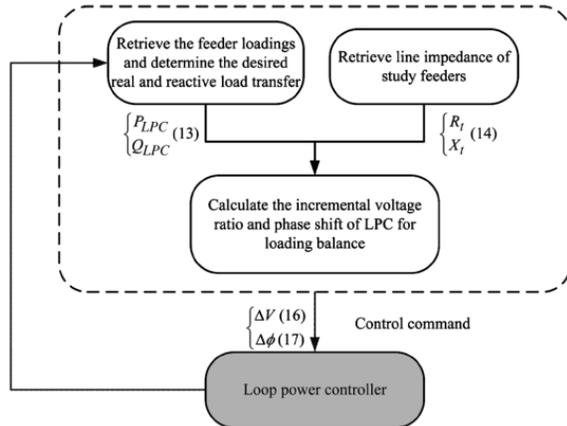


Fig. 2. Flowchart of LPC control algorithm

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

$$\begin{bmatrix} \bar{I}_s \\ \bar{I}_r \end{bmatrix} = \begin{bmatrix} |n|^2 \bar{y} & -\bar{n}^* \bar{y} \\ -\bar{n} \bar{y} & \bar{y} \end{bmatrix} \begin{bmatrix} \bar{V}_s \\ \bar{V}_r \end{bmatrix} \quad (1)$$

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

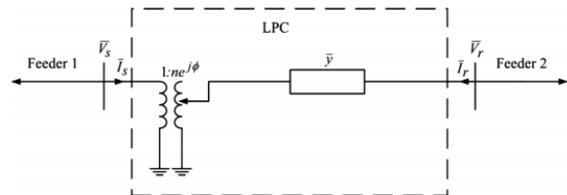


Fig. 3. Circuit model of loop power controller.

To simplify the process to determine the voltage ratio and phase shift of LPC, this paper proposes a modified equivalent circuit with dependent current sources and 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:

$$\begin{aligned} I_s &= n^2 \bar{y} \bar{V}_s - \bar{n} \bar{y} \bar{V}_r \\ &= (n^2 - 1) \bar{y} \bar{V}_s + (1-n) \bar{y} \bar{V}_r + \bar{y} (\bar{V}_s - \bar{V}_r) \end{aligned} \quad (2)$$

$$\begin{aligned} I_r &= -\bar{n} \bar{y} \bar{V}_s + \bar{y} \bar{V}_r \\ &= (1-n) \bar{y} \bar{V}_s + \bar{y} (\bar{V}_r - \bar{V}_s) \end{aligned} \quad (3)$$

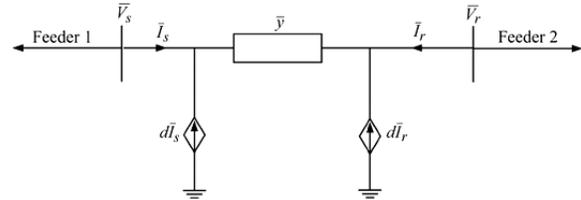


Fig. 4. Modified equivalent circuit model of LPC.

The equivalent injection currents are solved as

$$dI'_s = -(n^2 - 1) \bar{y} \bar{V}_s - (1-n) \bar{y} \bar{V}_r \quad (4)$$

$$dI'_r = -(1-n) \bar{y} \bar{V}_s \quad (5)$$

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:

$$\begin{aligned} I_s &= \bar{y} \bar{V}_s - \bar{y} e^{-j\varphi} \bar{V}_r \\ &= (1 - e^{j\varphi}) \bar{y} \bar{V}_r + \bar{y} (\bar{V}_s - \bar{V}_r) \end{aligned} \quad (6)$$

$$I_r = (1 - e^{j\varphi}) \bar{y} \bar{V}_s + \bar{y} (\bar{V}_r - \bar{V}_s) \quad (7)$$

The equivalent injection currents are solved as

$$dI''_s = -(1 - e^{-j\varphi}) \bar{y} \bar{V}_r \quad (8)$$

$$dI''_r = -(1 - e^{-j\varphi}) \bar{y} \bar{V}_s \quad (9)$$

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

$$dI_s = dI'_s + dI''_s \quad (10)$$

$$dI_r = dI'_r + dI''_r \quad (11)$$

$$\begin{bmatrix} d\bar{I}_s \\ d\bar{I}_{r0} \end{bmatrix} = \begin{bmatrix} (1-n^2) \bar{y} & (n + e^{-j\varphi} - 2) \bar{y} \\ (n-1) \bar{y} & (n + e^{j\varphi} - 2) \bar{y} \end{bmatrix} \begin{bmatrix} \bar{V}_s \\ \bar{V}_r \end{bmatrix} \quad (12)$$

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

B. LPC Control Algorithm

To illustrate the proposed control algorithm for LPC to achieve feeder loading balance, consider the two sample radial feeders connected with an LPC in Fig. 5. The desired real and reactive power flows through the LPC for feeder loading balance are defined as

$$\begin{cases} P_{LPC} = \frac{P_1 - P_2}{2} \\ Q_{LPC} = \frac{Q_1 - Q_2}{2} \end{cases} \quad (13)$$

If the branch impedances of Feeder 1 and Feeder 2 are (R_1, X_1) and (R_2, X_2) , respectively, the total impedance of two feeders is defined as

$$\begin{cases} R_t = R_1 + R_2 \\ X_t = X_1 + X_2 \end{cases} \quad (14)$$

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):

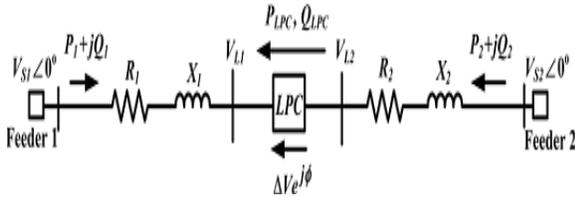


Fig. 5. Incremental circuit model of distribution feeders with LPC.

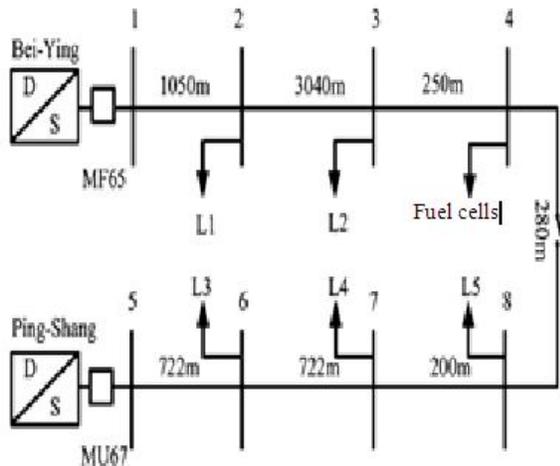


Fig.6. power distribution feeders for computer simulation.

$$\begin{aligned} |V'_{L2}| \\ = \sqrt{(1 + P_{LPC}R_t + Q_{LPC}X_t)^2 + (P_{LPC}X_t - Q_{LPC}R_t)^2} \end{aligned} \quad (15)$$

The incremental terminal voltage and phase shift are therefore calculated as follows:

$$\Delta V = |V'_{L2}| - 1.0 \quad (16)$$

$$\Delta \phi = \tan^{-1} \frac{P_{LPC}X_t - Q_{LPC}R_t}{1 + P_{LPC}R_t + Q_{LPC}X_t} \quad (17)$$

IV. CASE STUDY OF DISTRIBUTION SYSTEM

Fig. 7 shows the one-line diagram of the power system network. There are number of units of DC/AC inverters which are used to convert the fuel cell generation to Vac.

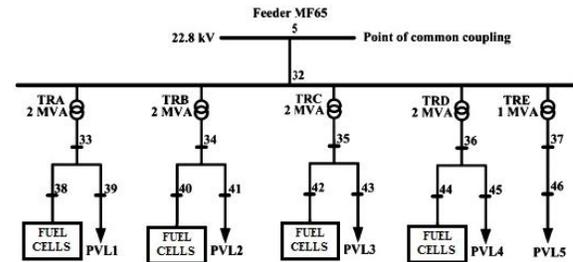


Fig. 7. One-line diagram of distribution system.

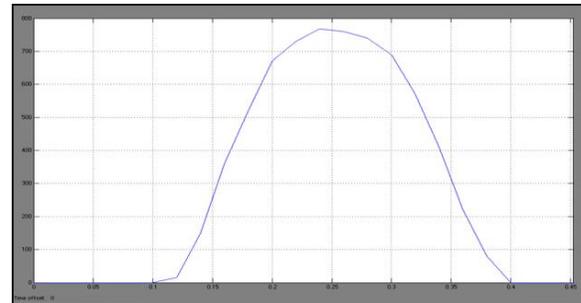


Fig. 8. Actual fuel cell power generation

The daily power generation of the study fuel cell system has been recorded by the SCADA system as shown in Fig. 8. It is found that the fuel cell power

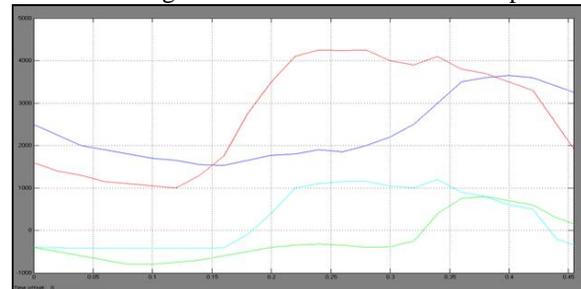


Fig. 9. Power profiles of Feeder MF65 and MU67 (without fuel cell system).

generation is increased.

Fig. 9 shows the daily profiles of real and reactive power loading of Feeders MF65 and MU67 without considering the power injection by the PV system.

The peak loading of Feeder MF65 was 3724 kW/1232 kVAR at 8 PM and the peak loading of Feeder MU67 was 4483 kW/1485 kVAR at 2 PM. Feeder MF65 serves the residential area with customers consuming most of the power demand during night time period when people stay at home with heavy air conditioner loading. Feeder MU67, however, serves the commercial area with customers consuming most of power demand during daytime business hours.

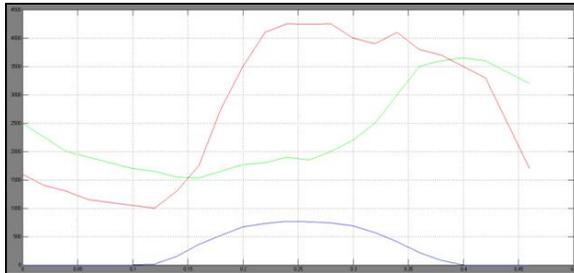


Fig. 10. Power profiles of Feeder MF65 and MU67 (with fuel cell system).

Fig. 10 shows the reduction of real power loading of Feeder MF65 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 fuel cell systems, an adaptive LPC control algorithm is derived to adjust

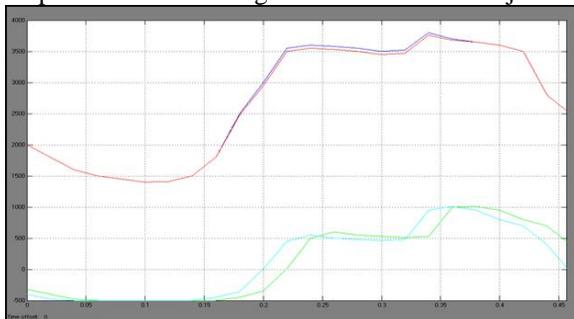
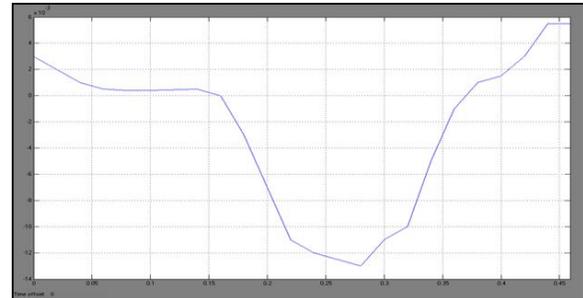


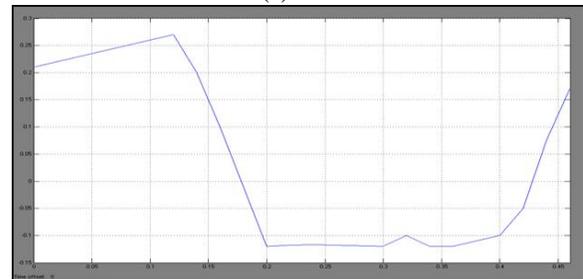
Fig. 11. Loading balance of both feeders with the control of LPC (w/o PV system).

the voltage ratio and phase shift between both feeders according to the feeder loading and fuel cell generation for each study hour. 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 MF65 and MU67 in Fig. 6. After executing the loading balance by LPC for the distribution system without considering the fuel cell

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 to achieve proper control of power transfer between both feeders. The differences of real power and reactive power loadings between Feeders MF65 and MU67 at 3 PM have been reduced from 1864 kW/1715 kVAR to 170 kW/71 kVAR after implementing LPC for power flow control.



(a)



(b)

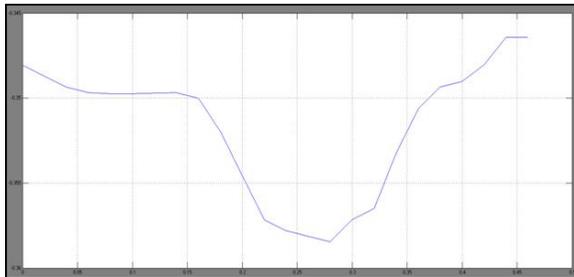
Fig. 12. Voltage ratio and phase shift for the power transfer by LPC (without the fuel cell system).

Fig. 12 shows the corresponding voltage ratio and phase shift for each study hour, which are derived in (16) and (17) for LPC control to achieve the load transfer between both feeders. At 3 PM, a phase shift of is applied for real power transfer of 1012 kW from MU67 to MF65 while the voltage ratio of -0.013 p.u. is applied for reactive power transfer of 890 kVAR from MU67 to MF65. On the other hand, a phase shift of 0.27 is used for real power transfer of 450 kW from MF65 to MU67 at 6 AM, and the voltage ratio of 0.001 p.u. is applied for reactive power transfer of 190 kVAR from MU67 to MF65.

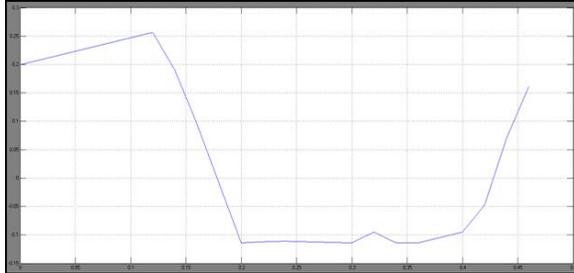
When the fuel cell system of Kaohsiung Stadium is integrated in the distribution system, the power loading of Feeder MF65 is reduced as fuel cell power generation is reduced. To achieve the loading balance, the voltage ratio and phase shift by LPC have to be revised as shown in Fig. 13 according to the variation of fuel cell power generation. By

comparing to Fig. 12, the voltage ratio of LPC remains the same because the fuel cell 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 fuel cell system is injected. For instance, a larger phase shift of -0.3° is applied for real power transfer of 897 kW from MU67 to MF65 at 3 PM. With the control of LPC, the loading balance of test feeders by including the fuel cell power generation has been obtained as shown in Fig. 14. By comparing to Fig. 10, the mismatches of real power and reactive power loadings between Feeder MF 65 and Feeder MU 67 at 3 PM are reduced from 2574 kW/1727 kVAR to 191kW/79 kVAR after loading balance.



(a)



(b)

Fig. 13. (a)Voltage ratio and (b)phase shift with the control of LPC (with fuel cell system).

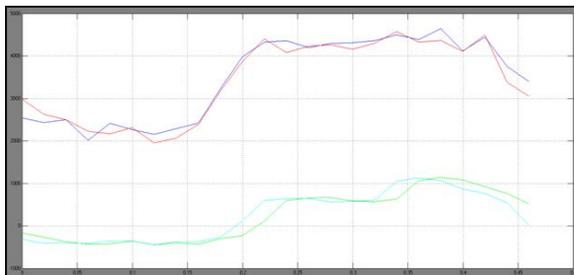


Fig.14. Loading balance of both feeders with the control of LPC (with fuel cell system).

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 MF65 and MU67 by considering the daily 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 analysis for each study hour. For the test distribution system with fuel cell system, Fig. 15 shows the system power loss as percentages of feeder loading. Without

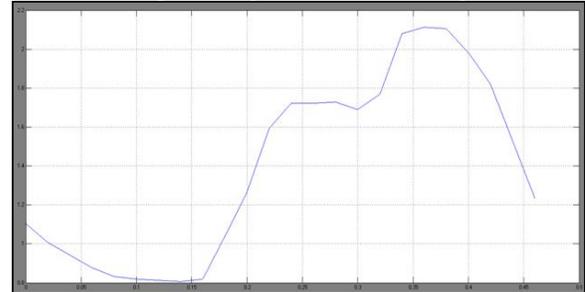


Fig. 15. Percentage of system power loss applying LPC for loading balance (with fuel cell system)

applying the LPC for loading balance, the feeder power loss varies from 1.2% of the feeder loading during the light load period to 3.3% during the peak load period. The power loss over the daily period is reduced from 3457 kWh (2.8%) to 2970 kWh (2.3%) after loading balance by LPC. The system power loss reduction has therefore been obtained after implementing the LPC for loading balance.

V. CONCLUSIONS

This study evaluates a power electronics-based loop power controller to replace the open-tie switch for the control of real power and reactive power transfer between distribution feeders to achieve loading balance of distribution system. The voltage ratio and phase shift adjusted by LPC are derived according to mismatches of real power and reactive power loadings between test feeders for each study hour. To demonstrate the effectiveness of LPC for the enhancement of loading balance, a distribution system consisting of two feeders with a large-scale fuel cell system has been selected for computer simulation. The power loadings of the study feeders and the fuel cell power generation have been recorded. 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 for each study hour. According to the computer simulation, it is concluded that the loading balance of



distribution systems with intermittent fuel cell power generation can be obtained effectively by the implementation of LPC to achieve adaptive control of load transfer between distribution feeders. The power loss reduction of test feeders after loading balance by LPC has also been derived in this paper.

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