SWU Engineering Journal (2018) 13(1), 202-211 วารสารวิศวกรรมศาสตร์ มหาวิทยาลัยศรีนครินทรวิโรฒ
ปีที่ 13 ฉบับที่ 1 เดือนมกราคม – เมษายน พ.ศ. 2561

Non-Line-Impedance-Synthesized Power Sharing Control in Microgrid Using On-Demand Power Feeding

Suchart Janjornmanit [1]* Suttichai Premrudeepreechacharn [1] Kohji Higuchi [2]
[1] Chiang Mai University. 239, Huay Kaew Road, Mueang District, Chiang Mai 50300, Thailand
[2] The University of Electro-Communication, 1-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan
*Corresponding author: Email: suchart@rmutl.ac.th

ABSTRACT

A method of power sharing control in the islanding operation of microgrid is proposed in this paper. The proposed approach formulates the power generation of each DG by the relationship of power-angle control, in which the magnitude and angle of the generating voltage are adjusted to follow the change of demanding power. By comparison to the previous work, the new method does not need the value of line impedance, connecting between DG and the common bus, to incorporate the control function. The method, limiting the output power and preventing power consumed by the DG, is also improved. The new method of power-angle control demonstrated that without using the knowledge of line impedance, the suitable power sharing point in the microgrid could also be tracked within each DG's capacity autonomously. Simulation and experimental results demonstrate the validity of the proposed control.

Keyword: Automatic generation control, distributed power generation, microgrids, power control, power sharing.

1. Introduction

Nowadays, microgrid is becoming a viable option for power generation since it distributes the autonomous energy supply. It provides a solution to the system where the energy demand is in the remote area and sometimes the power is disconnected from the public electricity. The Distributed Generation (DG) operated by power electronic converter, such as the Voltage Source Converter (VSC) , plays an important role in microgrid. In addition, the droop control technique is widely used for power sharing control in the islanding microgrid. In general, this technique emulates the power generated by the synchronous generator where the output voltage magnitude and frequency are adjusted linearly to the power. There are studies on droop control with minimum communication between DGs [1]-[4]. The works on droop control without using additional communication [5]-[7] are also published. There are studies of the droop [8]-[9] published recently, but the works need the knowledge of line impedance to incorporate into the formulation of the control. Although the power sharing by the droop gains intensive implementation, it is proven to have limitations [10]-[11]. The control of power output

by varying voltage magnitude and frequency itself creates the residual deviation in the interconnected system. Angle droop [12]-[14] is proposed to eliminate the residual frequency deviation; however, in this method the power is still varied linearly with the voltage magnitude and angle by the droop equation. In addition, the operation relies on the Global Positioning System (GPS). There is also a study of GPS synchronized droop control [15] published recently, but the formulation of the control based on the assumption that the line impedance is known. The power sharing by droop is problematic to the system with resistive line impedance [6], [10]-[11], [16]-[19]. The concept of virtual impedance [20]-[22] has been proposed and successfully implemented to overcome this problem. The concept is actually the reference voltage modification that introduces the line impedance into the control loop. However, choosing of virtual impedance is complicated, it requires a trade-off between power sharing and voltage regulation [11]. The power sharing control by the droop has been used for a long time. Although this technique achieves high reliability and flexibility, it has several drawbacks that limit its application [11].

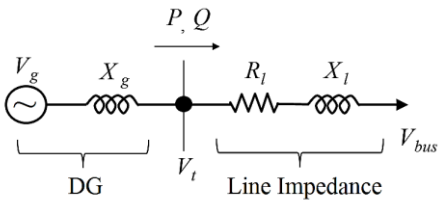


Fig. 1 Power delivery from DG to the bus.

In this research, the usage of droop control is eliminated. The idea of the power-angle control without incorporating the droop [23] is proposed firstly, but the method requires the value of line impedance to formulate the control function. The limitation is further improved by this work.

2. Power Sharing Analysis

Fig. 1 shows the power delivery from DG via a line to its connected bus.

The active power generation [24], P, of the DG can be calculated by:

$$P = \frac{|V_g|\,|V_t|}{X_g}\sin(\delta_g) \quad (1)$$

where V_g is the generating voltage, V_g is the voltage at DG's terminal, δ_g is the angle between V_g and V_t, and X_g is output inductance of the DG. In addition, the reactive power generation [24], Q, can be calculated by:

$$Q = \frac{|V_t|}{X_g}\left(|V_g|\cos(\delta_g) - |V_t|\right) \quad (2)$$

The assumption is that the angle δ_g is small and it can be inferred from the above equations that increasing δ_g causes a greater change in active power than reactive power. In addition, the reactive power is changed depending on the difference in voltage magnitude between V_g and V_g, called ΔV.

3. The Proposed Power-Angle Control using On-demand Power Feeding

By using (1), the relationship between active power generation and the angle difference, δ_g, can be rewritten as:

$$\delta_g \approx \sin^{-1}\left(\frac{PX_g}{(|V_{bus}|^*)^2}\right) \quad (3)$$

To simplify the operation, the magnitude of voltage at bus $|V_{bus}|^*$ is used instead of V_g and V_t in (1), and it is treated as a constant value, as the rated voltage on the bus, to determine the required constraint operation of the DGs. In addition, by using (2) the relationship between

reactive power generation and the voltage difference, ΔV, can be rewritten as:

$$\Delta V \approx \frac{QX_g}{|V_{bus}|^*} \quad (4)$$

To simplify further, $\cos(\delta_g)$ is omitted due to the fact that the angle is small.

The power in (3) and (4) can be calculated in every voltage cycle or updating round by:

$$P^i = \frac{V_{max}I_{max}\cos(\theta)}{2} \quad (5)$$

$$Q^i = \frac{V_{max}I_{max}\sin(\theta)}{2} \quad (6)$$

where the superscript i indicates the number of consecutive cycle or round of update. θ is the angle of power factor. V_{max} and I_{max} are voltage and current magnitude detected at DG's terminal.

In order to control the power generation to follow the change of demanding power, the change of power from previous updating round, ΔP and ΔQ, needs to be detected, which can be calculated by:

$$\Delta P = P^i - P^{i-1} \quad (7)$$

$$\Delta Q = Q^i - Q^{i-1} \quad (8)$$

As it can be seen from (3) that the active power generation has a direct relationship to δ_g; therefore, the control of active power generation by adjusting the angle difference δ_g can be calculated with:

$$\delta_g^i = \delta_g^{i-1} + \sin^{-1}\left(\frac{\Delta P X_g}{(|V_{bus}|^*)^2}\right) \quad (9)$$

The adjusting of the angle difference δ_g in this way is the determination to adjust the power sharing of each DG to the microgrid with the DG's constraint. The suitable power sharing point may not reach immediately, but rather for a number of updating rounds.

In addition, as it can be seen from (4) that the reactive power generation has a direct relationship to ΔV; therefore, the control of reactive power generation by adjusting the voltage difference P_m can be calculated by:

$$\Delta V^i = \Delta V^{i-1} + \frac{\Delta Q X_g}{|V_{bus}|^*} \quad (10)$$

The determination of the adjusting of ΔV in this way is also the same as the adjusting of δ_g in which it adjusts the power sharing of each DG to the microgrid with the DG's constraint.

Thus, in each round of updating cycle the reference voltage is generated by:

$$V_g(t) = \left(V_g^i + \Delta V^i\right)\sin\left(\omega t + \delta_g^i\right) \quad (11)$$

In order to avoid the exchanging power between DGs, or the power is consumed by the DG, the output power of each DG should be limited to its capacity. From Eq. (3), the maximum active power P_m can be translated into a maximum angle δ_{gm}, which can be expressed by:

$$\delta_{gm} \approx \sin^{-1}\left(\frac{P_m X_g}{(|V_{bus}|^*)^2}\right) \quad (12)$$

In each round of updating cycle, after the active power is detected, if the value of P is negative, δ_g is forced to increase a small degree (use +5% of δ_{gm} in this work), and if P is greater than its capacity, δ_g is forced to decrease a small degree as well (use -5% of δ_{gm} in this work). This creates a constraint of the power sharing to the microgrid so that the other DGs is perceived the limitation from the DG and the power generation is then adjusted in accordingly.

In the case of reactive power, the maximum reactive power Q_m is a maximum of voltage magnitude difference ΔV_m. From Eq. (4), it can be expressed by:

$$\Delta V_m \approx \frac{Q_m X_g}{|V_{bus}|^*} \quad (13)$$

In each round of updating cycle, after the reactive power is detected, if the value of Q is negative, V_g is forced to increase a small magnitude (use +5% of ΔV_m in this work), and if Q is greater than its capacity, V_g is forced to decrease a small magnitude as well (use -5% of ΔV_m in this work). This also creates a constraint of the power sharing so that the other DGs is perceived and the power generation is then adjusted in accordingly too.

A flowchart of reference voltage generation is showed in Fig. 2 and Fig. 3 shows VSC using the

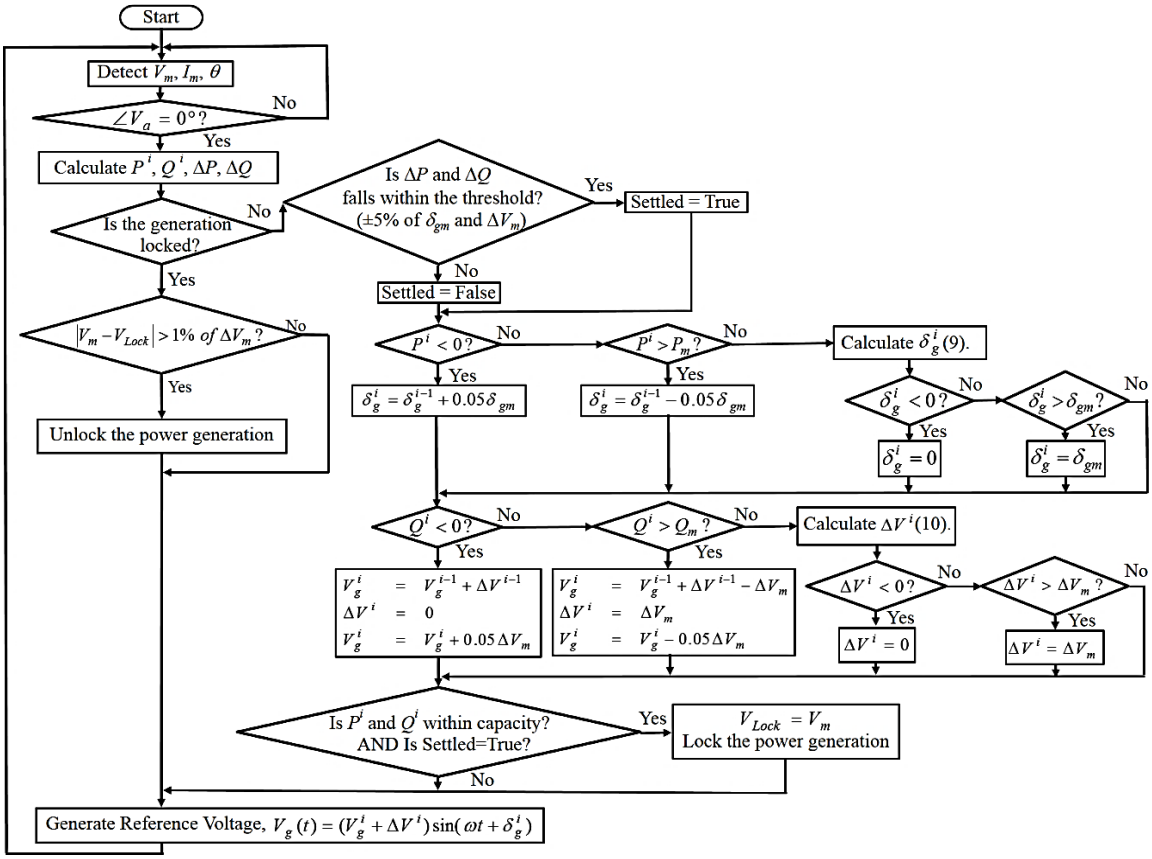


Fig. 2 Flowchart of the reference voltage generation.

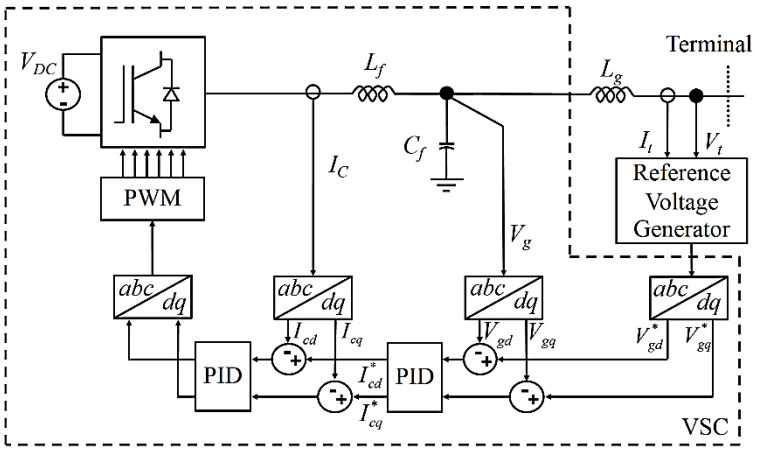


Fig. 3 A VSC with reference voltage generator.

reference voltage generator. The proposed analysis is based on the assumption that the load is balance. If the system is unbalanced, then all three lines need to be sensed and the proposed reference voltage generation may be formulated in the rotating d-q-0 coordinates, or at least the system should be separated to be three single- phase systems.

4. Simulation Studies

The simulation are performed using MATLAB /SIMULINK. The operation of the network is regarded as the islanding microgrid. The system is a 3-phase 380V/50Hz. The results are the locked values when the system is in the stable and steady-state power sharing point. All values are per unit with base MVA(1MVA) and the base kVLL(0.380). In order to compensate for voltage drop on the line, V_g at the beginning of the reference voltage generation should be higher than V_{bus}. In the simulations, V_g begins with 390V. In the simulation studies, the DG is simulated by ‘Controlled Voltage Source’ which means that there would not be voltage tracking error in the studies. The effect of voltage tracking error can be neglected when the error is minimal [23].

4.1. The Step Change of Load

Fig. 4 shows configuration of microgrid for this study. Table I gives parameters for systems under consideration.

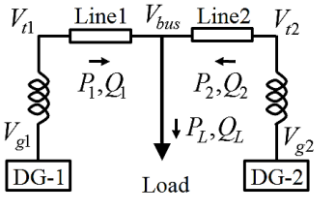
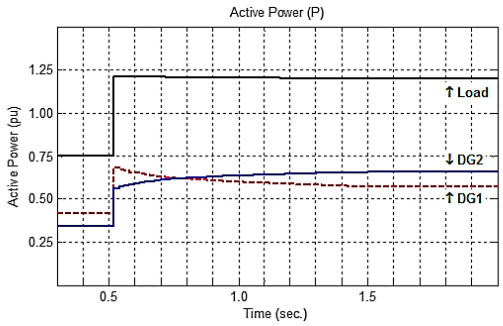


Fig. 4 Microgrid system under consideration.

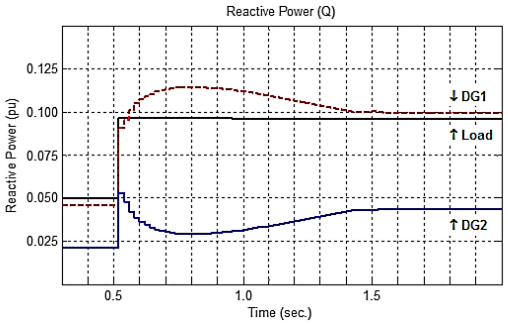
TABLE I System parameters (step load change)

Quantities	Values(pu)
Line1 impedance	0.125+j0.166
Line2 impedance	0.166+j0.208
Load rating(before)	P=0.75, Q=0.05
Load rating(after)	P=1.25, Q=0.1
DG-1 rating	P_{m1}=0.75, Q_{m1}=0.1
DG-2 rating	P_{m2}=0.75, Q_{m2}=0.1
Output inductance 1	j0.125
Output inductance 2	j0.125

The load begins by P_L=0.75pu and Q_L=0.05pu. The locked values before the load change are shown in Table II At 0.5 second, the load is step changed to P_L=1.25pu. and Q_L=0.1pu., and the simulation results during load changing are in Fig. 5(a) and 5(b). The simulation results of locked values after the load change are in Table III. The



(a)



(b)

Fig. 5 Results of the step load change, (a) result of active power, and (b) result of reactive

results indicate that the approach is able to control the power generation even when the load is suddenly changed. In addition, it has to be noted in Fig. 5(b) that after the load change the reactive power of DG- 1 are greater than its maximum capacity of 0.1, but the control is able to force the power down under its capacity.

TABLE II Results of step load change (before)

Quantities	Values(pu)
Result of DG-1 output	P_1=0.421, Q_1=0.0458
Result of DG-2 output	P_2=0.343, Q_2=0.0216
Result of load	P_L=0.751, Q_L=0.0501
Volt. at bus	V_{bus}=1.0039∠0°
Volt. at DG-1 output	V_{g1}=1.0281∠2.15°
Volt. at DG-2 output	V_{g2}=1.0271∠2.05°
Volt. at DG-1 terminal	V_{t1}=1.0234∠1.16°
Volt. at DG-2 terminal	V_{t2}=1.0237∠1.22°

TABLE III Results of step load change (after)

Quantities	Values(pu)
Result of DG-1 output	P_1=0.576, Q_1=0.1000
Result of DG-2 output	P_2=0.659, Q_2=0.0431
Result of load	P_L=1.198, Q_L=0.0994
Volt. at bus	V_{bus}=0.9824∠0°
Volt. at DG-1 output	V_{g1}=1.0195∠2.71°
Volt. at DG-2 output	V_{g2}=1.0268∠3.78°
Volt. at DG-1 terminal	V_{t1}=1.0113∠1.93°
Volt. at DG-2 terminal	V_{t2}=1.0203∠2.87°

4.2. Test of Meshed Network

Fig. 6 shows configuration of microgrid for consideration of meshed network. Table IV gives parameters for the system under consideration.

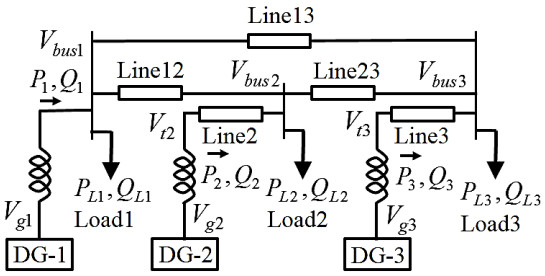


Fig. 6 Three-bus meshed network.

The simulation result of the three- bus meshed network are in Table V.

TABLE IV System parameters (meshed network)

Quantities	Values(pu)
Line1 impedance	- (Connected directly to the bus)
Line2 impedance	0.166+j0.021
Line3 impedance	0.332+j0.041
Line12 impedance	0.166+j0.208
Line13 impedance	0.021+j0.083
Line23 impedance	0.125+j0.166
Load1 rating	P=0.25, Q=0.05
Load2 rating	P=0.5, Q=0.1
Load3 rating	P=0.5, Q=0.05
DG-1 rating	P_{m1}=0.5, Q_{m1}=0.1
DG-2 rating	P_{m2}=1, Q_{m2}=0.2
DG-3 rating	P_{m3}=0.75, Q_{m3}=0.1
Output inductance 1	j0.125
Output inductance 2	j0.125
Output inductance 3	j0.125

It has been reported [11] that by far, the largest body of research work done in the decentralized microgrid control has been for radial network. The simulation results demonstrate that proposed method has a capability to control the power

sharing not only in the radial network, but also in the meshed network.

TABLE V Results of three-bus meshed network

Quantities	Values(pu)
DG-1 output	P_1=0.455, Q_1=0.0978
DG-2 output	P_2=0.511, Q_2=0.0633
DG-3 output	P_3=0.285, Q_3=0.0394
Bus1 to bus2	P_{L12}=0.029, Q_{L12}=0.0096
Bus1 to bus3	P_{L13}=0.175, Q_{L13}=0.0389
Bus2 to bus3	P_{L23}=0.036,Q_{L23}=-0.0271
Result of load1	P_{L1}=0.246, Q_{L1}=0.0493
Result of load2	P_{L2}=0.491, Q_{L2}=0.0982
Result of load3	P_{L3}=0.491, Q_{L3}=0.0491
V at bus1	V_{bus1}=0.9961∠0.26°
V at bus2	V_{bus2}=0.9939∠0.17°
V at bus3	V_{bus3}=0.9939∠0°
V at DG-1 output	V_{g1}=1.003∠71.35°
V at DG-2 output	V_{g2}=1.0282∠1.34°
V at DG-3 output	V_{g3}=1.0287∠0.63°
V at DG-1 terminal	V_{t1}=0.9961∠0.26°
V at DG-2 terminal	V_{t2}=1.0218∠0.18°
V at DG-3 terminal	V_{t3}=1.0250∠-0.03°

5. Experimental Results

In order to prove that the concept has a feasibility to be implemented in real microgrid, the proposed approach is tested in a down-scale single phase 220V/50Hz system.

Fig. 7 shows the configuration of the system of two DGs; all parameters are included in the figure. The system can be regarded as the system in Fig. 4. The parameters for the system in per unit with base kVA(0.3) and base kV(0.22), are in Table VI. To simplify the operation of the V_g tracking control, the V_g is controlled by a direct voltage-PWM control loop. The control functions of both DGs are operated by a single dSPACE system, but modules of the proposed power sharing control for each DG are separated.

There are problems related to the implementation of the VSC-type DG. The recommendation is given as follows for implementation of the proposed approach. If there are noisy environment, voltage fluctuation by controlling of VSC, and inaccuracy of the phase angle and peak detection, then the adjustment of power sharing by (9) and (10) may not be smooth and desirable. In order to mitigate those effects on power sharing, equation (9) and (10) need to be modified by adding a damping coefficient (C_d). Therefore, equation (9) is modified to be:

$$\delta_g^i = \delta_g^{i-1} + C_d \sin^{-1}\left(\frac{\Delta P X_g}{(|V_{bus}|^*)^2}\right) \qquad (14)$$

, where equation (10) is modified as:

$$\Delta V^i = \Delta V^{i-1} + C_d \frac{\Delta Q X_g}{|V_{bus}|^*} \qquad (15)$$

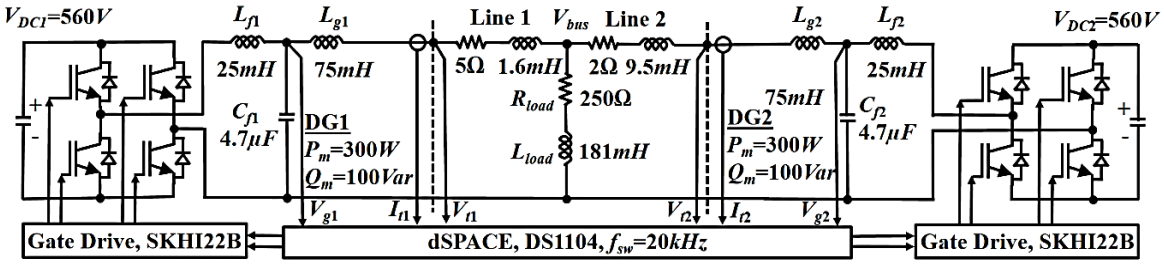


Fig. 7 Configuration of the experimental system.

The value of damping coefficient is between 0-1. For the system without any concerns about those effects, such as in the simulation study, C_d can be 1. The lower value of C_d is more mitigation of the effects on power sharing, but its response would be slower. In the experiment, it found that C_d= 0.2 is the optimal value in the test condition.

TABLE VI

System parameters (experimental system)

Quantities	Values(pu)
Line1 impedance	0.0310+j0.0031
Line2 impedance	0.0124+j0.0185
Load rating	P=0.613, Q=0.138
DG-1 rating	P_{m1}=1, Q_{m1}=0.333
DG-2 rating	P_{m2}=1, Q_{m2}=0.333
Output inductance 1	j0.146
Output inductance 2	j0.146

Table VII shows the results of the experiment in per unit and the parameters in the Table VI are the same values as in Fig. 7. Table VIII shows the results of the experiment of the previous work [23], in the same system. It can be noted that the results of power sharing are different between the two methods. This is due to the fact that the adjusting of V_g, ΔV and δ_g are different; whereas the previous work [23] need the value of line impedance to calculate the adjustment, this work does not need the value. The adjustment of each method leads to its own suitable power sharing point, which is different from each other.

6. Conclusions

This article proposes a method to control active and reactive power sharing in Microgrid. The proposed control is based on the power- angle control with on- demand power feeding. The presented technique is able to operate autonomously in islanding mode and in DG with either inductive or resistive line. The design of the control function is simple and it guarantees that there would not be the power consumed by the DGs. The experimental results show the validity that the proposed approach can be implemented in practices.

TABLE VII

Experimental results of the proposed method

Quantities	Values(pu)
DG-1 output	P_1=0.459, Q_1=0.016
DG-2 output	P_2=0.161, Q_2=0.128
Result of load	P_L=0.615, Q_L=0.140
Voltage at bus	V_{bus}=1.0002$\angle 0^o$
V at DG-1 output	V_{g1}=1.0173$\angle$4.10^o
V at DG-2 output	V_{g2}=1.0182$\angle$1.73^o
V at DG-1 terminal	V_{t1}=1.0141$\angle$0.05^o
V at DG-2 terminal	V_{t2}=1.0041$\angle$0.08^o

TABLE VIII

Experimental results of the previous work [23]

Quantities	Values(pu)
DG-1 output	P_1=0.276, Q_1=0.003
DG-2 output	P_2=0.343, Q_2=0.149
Result of load	P_L=0.6166, Q_L=0.141
Voltage at bus	V_{bus}=1.0032$\angle 0^o$
V at DG-1 output	V_{g1}=1.0110$\angle$1.96^o
V at DG-2 output	V_{g2}=1.0296$\angle$2.59^o
V at DG-1 terminal	V_{t1}=1.0109$\angle$-0.35^o
V at DG-2 terminal	V_{t2}=1.0100$\angle$-0.15^o

7. Acknowledgements

This research was performed partly under the National Research University Project, Office of the Higher Education Commission, Thailand and Chiang Mai University. The authors would like to thank National Science and Technology Development Agency and Rajamangala University of Technology Lanna for scholarship and support for studying.

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