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A New Algorithm for Load Flow Analysis in Autonomous Networks

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Abstract

In this paper, a novel algorithm for the load flow analysis problem in an islanded microgrid is proposed. The problem is modeled without any slack bus by considering the steady state frequency as one of the load flow variables. To model different control modes of DGs, such as droop, PV and PQ, in an islanded microgrid, a new formula for load flow equations is proposed. A hybrid optimization algorithm, named (ICGA), is developed, based on imperialist competitive algorithm (ICA) and genetic algorithm (GA) thinking, to minimize the total active and reactive power mismatch in the islanded microgrid. The performance of the proposed algorithm is compared with the GA, Newton-trust and time domain methods. The results provide support for the validity of the paper algorithm.

Keywords: Transient Microgrid, Load flow, ICGA, Optimization, Distributed generation.
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Nomenclature

HMS	*Harmony memory size*
PAR	*Pitch adjusting rate*
HMCR	*Harmony memory considering rate*
BW	*Distance bandwidth*
t	*Time index*
N_{obj}	*Number of objective functions*
N_{rep}	*Number of solutions in repository*
κ_i	*The decision maker preference for all objective functions.*
δ_i	*Phase angle of voltage at bus i*
I_i, $I_i^{\max}$	*Current and rated current of line i*
$S_{gi}^{\max}$	*Maximum apparent power of* DG_i
$P_{DGi}^{\max}$	*Maximum active power of* DG_i
$Q_{DGi}^{\max}$	*Maximum reactive power of* DG_i
P_j	*Injected active power to bus j*
Q_j	*Injected reactive power to bus j*
$C_m(P_{DGi})$	*Fuel consumption of* DG_i
$\hat{P}_{i+1}, \hat{Q}_{i+1}$	*Total active and reactive power at bus i +1*
N_{dr}	*Number of DGs with droop control*
$\lvert V_i^* \rvert$	*Voltage magnitude of* DG_i *at no load*
ω_i^*	*Angular frequency of* DG_i *at no load*
S_p, S_q	*Active and reactive power static droop gain*
$Y_{ij}(\omega)$	*The* ij^{th} *element of admittance matrix*
θij	*Phase angle*
V_{min}, V_{max}	*Minim and maximum bus voltage*
NB	*Number of buses*
P_i , Q_i	*Demand active and reactive power of bus i*
R_i , X_i	*Resistance and reactance of line i*
P_{gi} , Q_{gi}	*Active and reactive power delivered to bus i*

1. Introduction

A Microgrid is seen as an interconnection of distributed generations (DGs) which is integrated with electrical and thermal loads as well as energy storages, and it operates as a single small scale system in low-voltage distribution systems. In microgrids, power quality, reliability and security can be increased by the use of power electronic interfaces and controls [1-3]. A microgrid might operate in grid-connected or islanded modes. In a grid-connected mode, the voltage and frequency of microgrids are dictated by the main grid while in an islanded mode control units of DGs along with managing active and reactive power are responsible for frequency and voltage regulation. This is appropriate for small microgrids where DGs are relatively close together [3-5]. Comparing with small microgrids, large microgrids with a large geographic domain might be controlled by decentralized strategies, such as droop control, as considerable communication is not required in large microgrids [2]. Locally measured variables, in droop control schemes, might be used for sharing of load demand among DGs effectively. This is to control the frequency and voltage of microgrids [6].Typically, power flow analysis of an electric power system involves computing the voltage of nodes and the amount of power flow through lines of a given load profile. A number of studies have proposed different power flow analysis models to address characteristics of distribution systems and microgrids, including high R/X ratios, radial or weakly meshed topologies and a large number of branches and nodes. Some of such analysis models are based on the traditional methods [7-12]. In [13] present a modified method, called backward/forward sweep method, for the Newton's approach to solve the power mismatch equations. Chen et al., give an implicit Z-Bus method for the power flow problem by adopting a superposition principle in which only one source for any given time is considered [14]. In [15] and [16], develop models for synchronous generators as well as voltage source inverter interface of DGs based on sequence components of a three-phase power-flow analysis model. In [16], presents a three-phase power flow analysis model to adopt real characteristics of islanded microgrids and those of three-phase distribution networks. Beside of the above analysis models, a number of studies have looked at power flow analysis models based on evolutionary algorithms which are independent of the initial values of the problem variables [17-19]. Interestingly, a review of the literature on load flow analysis reveals few studies are thinking in terms of considering the system frequency constant, despite the fact that, in an islanded microgrid, where there is no slack bus assuming steady state frequency constant is not correct and such steady state frequency should be considered as a load flow variable. In addition, load flow analysis studies generally consider DG units as PV or PQ nodes and they fail to deal with the operation of an islanded microgrid.

This paper proposes a novel load flow algorithm to model different control modes of DGs, such as droop, PV and PQ, in an islanded microgrid. The paper also proposes a new formula for load flow equations which is able to consider frequency as a variable. For this purpose, a droop control mode for DGs operation is first considered. Then, other DGs operation modes are involved. The system frequency and local voltage of each bus of DGs is next determined based on droop controller. This is followed by calculating the active and reactive power generated by e DGs to reflect the reality of decentralized droop control based on the operation of islanded microgrid. Finally, the voltages and angles of other buses of the islanded microgrid are calculated based on an iteration process to minimize the total active and reactive power mismatch.

This paper will be relevant to academics and practitioners interested in the management of microgrids. It provides a solution for the load flow analysis problem without consideration of any slack bus; contributing to the current practices of microgrid power management. The paper provides an understanding in the analysis of load flow problem wider than currently available. The paper algorithm is applicable to the analysis of islanded microgrids with different numbers of DGs and with different operation modes.

The order of presentation in this paper is as follows. Firstly, different microgrid models are discussed. Then the problem formulation is given. This is followed by the development of the proposed algorithm. Finally, the validation of the proposed algorithm is provided.

2. Microgrid Modelling

A) *Load Models*

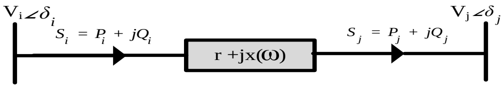
In the study of power systems, load models are typically assumed to be voltage independent and, therefore, the demand of active and reactive power is assumed to be constant [20]. Such assumptions, however, are not valid in practice, particularly for microgrids where some loads are dependent to voltage or frequency. Voltage and frequency dependent loads might, mathematically, be shown by [21],

$$P_L = P_0 (V)^{\alpha} (1 + K_{pf} \Delta\omega). \tag{1}$$

$$Q_L = Q_0 (V)^{\beta} (1 + K_{qf} \Delta\omega). \tag{2}$$

– *Branch Models*

A branch model for islanded microgrids may consist of a sending end bus (bus i) and a receiving end bus (bus j), as shown in Fig. 1. The line impedance in such models can be obtained by, z = r + j x (ω). In a branch of microgrids, power is able to flow any direction where the amount of power flow of both sending and receiving end buses are different and they are dependent on phase angles and voltage magnitudes of these two buses (Vi, δ i, Vj, δ j).



A branch model of islanded microgrids

– *DG Models*

In grid-connected modes of microgrids, DG sources might operate in pre-determined active and reactive power to fulfill load demands. The difference between the power produced by DGs and the total load demand, in such modes, might be either absorbed or supplied by the main grid. This can hold the voltage and frequency of all buses constant. In a grid-connected mode, similar to conventional power systems, DG buses can be treated as a PQ or PV bus [22-23]. However, this is not applicable to the islanded mode of operation, as discussed below:

- An islanded microgrid has no slack bus.
- All DGs are relatively small and they are not able to behave like a slack bus to stabilize and to hold the system frequency constant.
- The voltage of main grid does not exist to be used as a reference for the system voltage and the system frequency.
- Any mismatch between the power demand and production might lead to frequency and voltage deviations in an islanded mode.

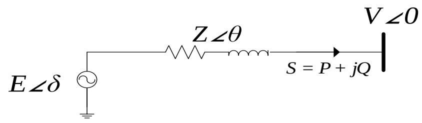
Thus the power flow problem should be solved without consideration of slack buses. To formulate the power flow problem without any slack bus a new droop controlled bus, applicable to islanded microgrids, needs to be developed. Such new droop bus is additional to the PQ bus, when the DG bus operates in a constant power factor, and it is also additional to the PV bus when the DG bus operates at a constant voltage (using voltage regulators) [24]. In a droop bus, the sharing of active and reactive power between DG sources can be calculated based on droop characteristics of controllers. This is imitated from the performance of large synchronous generators in conventional networks. Based on the droop controller characteristics, a decrease in frequency and voltage amplitude follows from an increase in active power and reactive power, respectively. There follows in a droop controlled bus, the apparent, active and reactive power flow to the interconnection line, can be calculated by (see Fig. 2),

$$S = E \angle \delta \left[\frac{\left(E \angle \delta - V \right)^{*}}{Z \angle \theta} \right]. \qquad (3)$$

By assuming a small value for δ, the value of active and reactive power can be, respectively, obtained by,

$$P = \frac{V}{Z} [(E \cos \delta - V) \cos \theta + E\delta \sin \theta]. \qquad (4)$$

$$Q = \frac{V}{Z} [(E \cos \delta - V) \sin \theta - E\delta \cos \theta]. \qquad (5)$$



Equivalent circuit of a DG unit connected to a common AC bus

The output impedance of the converter is mainly inductive due to the coupling inductor utilized at the converter output [25-26]. Accordingly, the phase angle (θ) should be close to 90^0, and, therefore, Equations (4) and (5) can be simplified to,

$$P = \frac{V}{Z} E\delta. \qquad (6)$$

$$Q = \frac{V}{Z} (E - V). \qquad (7)$$

Equations (6) and (7) show that active power is a function of power angle δ while reactive power is a function of voltage magnitude. There follows, active and reactive power can be adjusted independently by controlling the frequency and magnitude of the output voltage of inverter, respectively. Equations (6) and (7), based on P–ω and Q–V droop controls, can be rewritten, respectively, by,

$$\omega = \omega^{*} - S_p P. \qquad (8)$$

$$V = V^{*} - S_q Q. \qquad (9)$$

The value of S_p and S_q can be obtained, respectively, by,

$$S_p = \frac{\Delta\omega}{P_{DGm}}. \qquad (10)$$

$$S_q = \frac{\Delta V}{Q_{DGm}}. \qquad (11)$$

To share the load among DG units, based on droop control, the following equations need to be satisfied [27-28],

$$S_{p_1} P_{DGm1} = S_{p_2} P_{DGm2} = \dots = S_{pi} P_{DGmi}. \qquad (12)$$

$$S_{q_1} Q_{DGm1} = S_{q_2} Q_{DGm2} = \dots = S_{qi} Q_{DGmi}. \qquad (13)$$

Using Equations (8) and (9), a DG, operating with droop control, can be obtained by,

$$P_{DGi} = \frac{1}{s_{p_i}}(\omega_i^* - \omega). \tag{14}$$

$$Q_{DGi} = \frac{1}{s_{q_i}}(V_i^* - V_i). \tag{15}$$

To share active and reactive power among DGs, the relationships of $P\text{-}\omega$ and $Q\text{-}V$, $P\text{-}V$ and $Q\text{–}\omega$, or $P\text{-}V\text{-}\omega$ and $Q\text{-}V\text{-}\omega$ might be used depending on converter impedance [29-30].

B) *Problem Formulation*

Solving the power flow problem determines four main variables, voltage angle, voltage magnitude and active and reactive power of PQ, PV and droop buses. For a PQ bus, the values of active and reactive power are known while the values of angle and magnitude of voltage are unknown. In comparison, in a PV bus the values of voltage and active power are known while in a droop bus all variables are unknown. Compared with conventional methods, in this study the electrical frequency is considered as an unknown variable in an islanded microgrid.

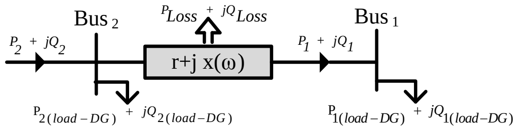
– *Calculation of PQ Bus Variables*

In a PQ bus, the values of received active and reactive power are known. There follows that a power flow analysis model needs to calculate the bus phase angle and voltage magnitude. In this paper, the model of Venkatesh and Ranjan is employed and modified to deal with PQ buses [30]. Following Venkatesh and Ranjan, the value of bus phase angle and voltage magnitude can be obtained, respectively, by,

$$V_j^2 = \sqrt{\left([rP_j + x(\omega).Q_j - \frac{V_i^2}{2}]^2 - [r^2 + x^2].[P_j^2 + Q_j^2]\right)} - [rP_j + x(\omega).Q_j - \frac{V_i^2}{2}]. \tag{16}$$

$$\delta_j = \delta_i - \sin^{-1}\left(\frac{x(\omega)P_j - rQ_j}{V_i V_j}\right). \tag{17}$$

where the notation and symbols are the same as those of Fig. 1. In Equations (16) and (17) the values of the following variables need to be given: the receiving end bus reactive power, the sending end bus phase angle and voltage magnitude, and the line impedance between the two buses. In Fig. 3, P_j and Q_j, j = 1 and 2, present the injected active and reactive power at each bus.



Difference among receiving and injection bus power

– *Calculation of PV Bus Variables*

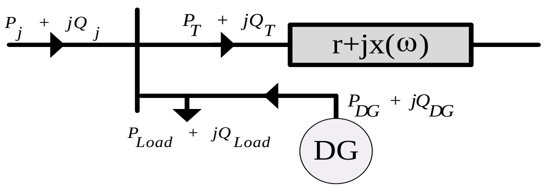
Using Equation (16) the value of reactive power injection of the PV bus can be obtained by,

$$Q_j = \frac{-2V_j^2 x(\omega) + \sqrt{\left(2V_j^2 x^2(\omega) - 4(r^2 + x^2(\omega))(V_j^4 - V_i^2 V_j^2 + (r^2 + x^2(\omega))P_j^2 + 2V_j^2 P_j r\right)}}{2(r^2 + x^2(\omega))}. \tag{18}$$

where the reactive power of the DG unit at the receiving end bus can be calculated by,

$$Q_{DG} = -Q_j + Q_{load} + Q_T. \tag{19}$$

as shown in Fig. 4. In Equation (19), the value of phase angle and Q_j can be calculated, respectively, by Equations (17) and (18). Such calculations are only valid where the value of Q_j is within the limited range of generator’s reactive power. Otherwise, Q_j needs to be treated as a known variable in which its value is equal to one of the boundary values of the limit corresponding to DG, (Q_{DG}). There follows that the receiving end bus is required to be converted from a PV bus to a PQ bus for the rest of the current iteration. For the next iteration, the receiving end bus needs to be considered again as a PV bus while the voltage is set to the value obtained in the preceding iteration.



Injected power of DG to bus j based on PV

– *Calculation of droop bus variables*

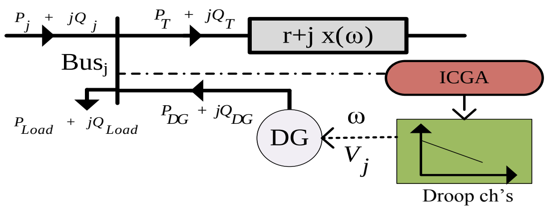
Unknown variables of a droop bus, as shown in Fig. 5, might be outlined as active and reactive power, voltage magnitude and angle. The values of power injection of bus j, shown in Fig 5, can be given by,

$$P_j = -P_{DG} + P_{load} + P_T. \tag{20}$$

$$Q_j = -Q_{DG} + Q_{load} + Q_T. \tag{21}$$

where the generated active and reactive power of DG units can be calculated by Equations (14) and (15), respectively.

To calculate the receiving end bus phase angle, Equation (17) can be used where P_j and Q_j are given by Equations (20) and (21). This is valid for the case where P_j and Q_j are within the permitted limit of DG units. Otherwise, P_j and Q_j need to be treated as known variables in which their values are equal to their corresponding limit values. There follows the receiving end bus is converted from the droop control mode to the PQ mode. Therefore, the power flow problem needs to be resolved for the bus phase angle and voltage magnitude.



Injected power of DG to bus j based on droop

– *Optimization*

To cope with the proposed load flow problem formulation, an optimization problem is developed. The objective is to minimize the sum of absolute mismatch values of active and reactive power,

$$f(x,u) = k_1 \left| \sum_{i=1}^{n_{bus}} \Delta P_i \right| + k_2 \left| \sum_{i=1}^{n_{bus}} \Delta Q_i \right| . \tag{22}$$

where $\boldsymbol{x}$ and $\boldsymbol{u}$ are the vectors of state and control variables, and they can be calculated, respectively, by,

$$\boldsymbol{x} = [\delta \quad V_L^{PQ} \quad Q_{DG}^{PV} \quad P_{DG}^{DR} \quad Q_{DG}^{DR}]. \tag{23}$$

$$\boldsymbol{u} = [\omega \quad V_1^{DR} \quad \ldots \quad V_N^{DR}]. \tag{24}$$

$$\Delta P_i = P_{DG_i} - P_{load\,i} - \sum_j V_i V_j Y_{ij}(\omega)\cos(\delta_i - \delta_j - \theta_{ij}) \tag{25}$$

$$\Delta Q_i = Q_{DG_i} - Q_{load_i} - \sum_j V_i V_j Y_{ij}(\omega)\sin(\delta_i - \delta_j - \theta_{ij} \tag{26}$$

There are two constraints in the optimization problem: voltage and frequency. The voltage magnitudes of droop bus are limited between two values dictated by physical restrictions,

$$V_{\min}^{DR} \le V \le V_{\max}^{DR} . \tag{27}$$

Similarly, system frequency magnitudes are limited between two values, namely $\omega_{\min}$ and $\omega_{\max}$, dictated by microgrid restrictions,

$$\omega_{\min} \le \omega \le \omega_{\max} . \tag{28}$$

3. Proposed Optimization Solution

A hybrid optimization algorithm, named (ICGA), is developed, based on imperialist competitive algorithm (ICA) [33], and genetic algorithm (GA) thinking [31], to solve the optimization problem. Using ICA, system frequency and local voltage at each bus of the DG unit is obtained based on the droop controller by calculating the cost value of colonies and the imperialist in each empire. To make a new set of colonies in the total search spaces GA, including mutation and crossover operators, is employed. The use of GA assists in having appropriate objective function values for the imperialist. The main steps of ICGA are outlined as follows.

STEP 1 (Initialization):

- ✓ Read information of the island microgrid.
- ✓ Generate an initial population by ICA (system frequency and local voltage at each bus of the DG unit based on the droop controller).

STEP 2: Load flow calculation.

STEP 3 (Objective function calculation):

- ✓ Calculate the value of objective function to minimize the total active and reactive power mismatch based on Eq. 22.

STEP 4 (Updating control vector):

- ✓ Sort the initial population based on the value of objective function.
- ✓ Select colonies and imperialists.
- ✓ Generate empires.
- ✓ Move the colonies toward their relevant imperialist (Assimilating).
- ✓ Randomly modify the position of some colonies (Revolution).
- ✓ If there is a colony in an empire which has lower cost than that of imperialist, swap the positions of that colony and the imperialist.
- ✓ Create a new population for GA to set each empire (an imperialist and its colonies) like parents in GA.
- ✓ Generate new colonies by the crossover (CR) and mutation (F) operators of GA.
- ✓ Swap the position of a colony and its imperialist by using GA if the colony objective function is lower than that of the imperialist.
- ✓ Load flow calculation
- ✓ Calculate the objective function for all empires based on Eq. 22.
- ✓ Find the weakest colony from the weakest empire and give it to the empire with the most

likelihood to possess the weakest colony (imperialist competition).

- ✓ Eliminate the powerless empires.

STEP 5 (Calculation ending):

- ✓ Stop if only one empire left, otherwise go to Step 2.

To solve the load flow analysis problem an algorithm is developed in two loops, namely, main loop and inner loop. The main loop is responsible for finding the optimal solution of the objective function and the inner loop is for calculating the load flow. In the proposed algorithm, in the first iteration, the value of control vector, ***u***, is assumed in the main loop. Then, in the inner loop, the value of state vector, ***x***, is calculated. Next the value of objective function is obtained and the value of ***u*** is modified accordingly. The iterations are controlled by a stopping criterion. The steps of the proposed method are outlined as follows.

- Initialization: In the main loop, for the first iteration, ICGA provides the initial values of local voltage of each droop bus and the frequency of the system; that is the control vector, ***u***.
- Load flow calculation: The calculated values of ***u*** are, then, served to the inner loop to calculate the unknown variables, the state vector **x**, corresponding to bus type (PQ, PV or Droop).The load flow analysis (inner loop), is ended when the number of iterations reach the considered maximum limit. Following Venkatesh and Ranjan (2003), the load flow calculation starts from a terminating microgrid branch (the last bus) and it continues towards the first bus (bus 1) [30].
- Objective function calculation: The calculated values of ***x*** are used for obtaining the objective function as presented in Eq. (22).
- Updating control vector: The value of objective function is used by ICGA for updating the values of ***u*.**
- Calculation ending: Based on an ending criterion, for example convergence of values, Step 2 is repeated or the calculation is ended.

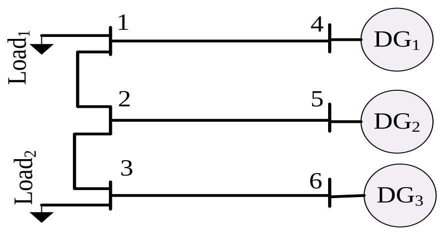
It should be noted that previous load flow analysis methods treat the values of local voltage and frequency as predetermined values and they fail to consider local voltage and frequency as unknown variables. The novelty of the method presented in this paper is that voltage and frequency are considered as unknown variables where the initial values of such variables are obtained by ICGA.

4. Case Studies

Two case studies (test systems) were investigated to validate the proposed load flow algorithm. These case systems were simulated in MATLAB. The following outlines the case studies. Table 1 presents the parameters of ICGA.

A) Case study#1:

The first system is a 6-bus system with rated voltage of 127, as shown in Fig. 6. This system operates in an islanded mode and consists of three similar droop control DGs, setting on buses 4, 5 and 6. The specifications of droop are given in Table 2. The load and line data of the system are based on the method of [16]. The performance of the proposed algorithm was compared with that of the time domain simulation in the PSCAD software [32], the ICA method, and the method used in [16]. The corresponding results are shown in Table 3. Figs.7 and 8 compare the magnitude and the average of phase errors of the three methods with those of the time domain simulation method, respectively. Figs. 7 and 8 show that the phase and magnitude errors of ICGA are the lowest while those of ICA are the highest. These figures show the lowest errors for the results of ICGA compared with those of GA and Newton-trust demonstrating a good performance for the proposed load flow algorithm in islanded mode of operation of microgrids based on droop controller. The steady state frequency obtained by the proposed method was 0.9992 p.u. A small deviation of frequency is due to the active power sharing among different DGs.



A 6-bus island microgrid test system

Table.1.
The ICGA, ICA and GA parameters

Method	*Pop. Size*	*CR*	*F*	*β*	*γ*	*ε*
GA	25	0.3	0.5	---	---	---
ICGA	Countries=10 Imperialists =5 GA=10	0.4	0.5	0.63	0.05	0.07
ICA	Countries=10 Imperialists =5	---	---	0.63	0.05	0.07

Table.2.
Setting of DG units in a 6-bus-system

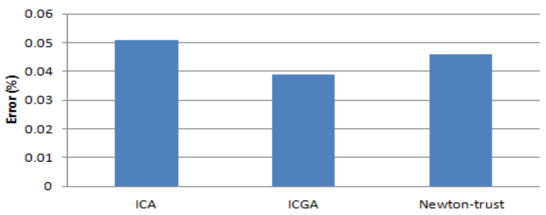
DG	*Location*	S_p	S_q	$\omega*$	V^*	S_{max}	Q_{max}
1	4	1.1439*10E-3	0.0591	1	1.01	1	0.7
2	5	1.1439*10E-3	0.0591	1	1.01	1	0.7
3	6	1.1439*10E-3	0.0591	1	1.01	1	0.7

Table.3.
Results of proposed algorithm for a 6-bus-system compared with other methods

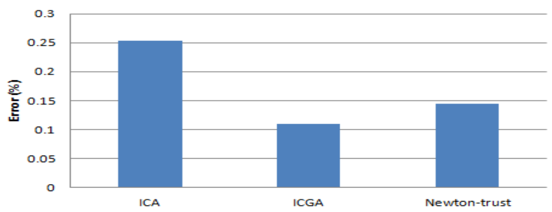
DG	Location	S_p	S_q	ω^*	V^*	S_{max}	Q_{max}
1	26	0.705*10E-3	0.0167	1	1.02	3.0	1.8
2	22	2.252*10E-3	0.0500	1	1.02	1.0	0.5
3	25	4.504*10E-3	0.0100	1	1.02	0.5	0.3
4	9	3.003*10E-3	0.0667	1	1.02	0.75	0.45

Table.4.
Setting of DGs in a 33-bus system

Bus	Time domain model [32] V (p.u., degree)		ICGA V (p.u., degree)		ICA V (p.u., degree)		Newton-trust [16] V (p.u., degree)	
1	0.9605	0.0000	0.9603	0.0000	0.9602	0.000	0.9601	0.0000
2	0.9730	-0.5270	0.9728	-0.5269	0.9726	- 0.5281	0.9725	-0.5262
3	0.9643	-2.6850	0.9645	-2.6849	0.9636	- 2.6786	0.9638	-2.6822
4	0.9877	-0.0725	0.9874	-0.0725	0.9875	-0.0723	0.9873	- 0.0722
5	0.9906	-0.4520	0.9908	-0.4520	0.9903	-0.4510	0.9901	- 0.4510
6	0.9698	-2.8690	0.9700	-2.8691	0.9702	-2.8679	0.9694	-2.8653



Average of magnitude error of different methods

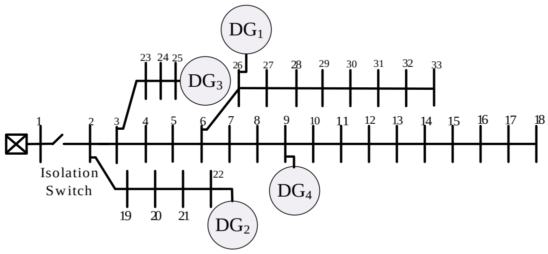


Average of phase error of different methods

C) *Case study#2:*

The second system is a 33-bus microgrid, shown in Fig. 9, with the rated voltage of 12.66 KV [31]. Four DGs were set on buses 26, 22, 25 and 9. Table 4 shows the static droop coefficients of DGs as well as the location, nominal setting, and rating of system. The coefficients K_{pf} and K_{qf} were set on 1 and -1, respectively. The steady state frequency, obtained by the proposed algorithm, is 0.99845 p.u.

Typically, a constant load is considered in power analysis methods. In this paper, however, following [7], the active and reactive power of commercial, residential, and industrial loads were calculated by Equations (1) and (2). Table 7 gives the voltage and load profiles in each bus. The values of active and reactive power, generated by DGs, are illustrated in Table 5. The values of generated power of DGs as well as the power demands and losses of system are presented in Table 6.



A 33-bus islanded microgrid system

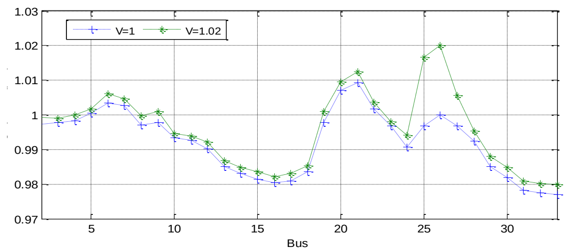
Table.5.
Power generated by DGs in a 33-bus microgrid

P_{DG}	Q_{DG}	P_{Loss}	Q_{Loss}	P_{Load}	Q_{Load}
3.717	2.286	0.0441	0.0225	3.6730	2.2635

Table.6.
Generated power, demands and losses of a 33-bus microgrid (P (MW) and Q (Mvar))

Sources	DG_1	DG_2	DG_3	DG_4
Active power (MW)	2.180	0.683	0.342	0.512
Reactive power (Mvar)	1.302	0.292	0.300	0.392

Fig. 10 shows the voltage profile of the 33-bus system. It is assumed that DG_1 operates in the PV mode with 2.1838 p.u. injection active power while other DGs operate in the droop mode. Two cases are studied: one with voltage of bus 26 equals 1 p.u. and the other equals 1.02 p.u.



Voltage profile when DG_1 operates in the PV mode

5. Discussion

In this paper, a new algorithm for the load flow analysis problem was proposed. The idea was to deal with the problem of the conventional load flow analysis, which is not able to cope with the case of isolated microgrids. The following clarifies the benefits of the proposed load flow algorithm compared conventional methods. In conventional methods, one DG operates in a PV mode while other DGs operate in a droop control mode. In practice, the selection of an appropriate setting for the voltage of the PV bus is crucial. This is to guarantee suitable reactive power sharing among droop DGs and to keep the voltage of the PV bus within the specified limits. Case study 2 shows the sensitivity of power flow against the setting of the voltage of a PV bus. Three values were considered for the voltage of a PV bus; less than 1 p.u., 1 p.u. and 1.02 p.u. The results show that, Fig. 11, when the voltage of the PV bus is less than 1 p.u., under-voltage can happen at majority buses of the network. Also the results show that for 1 p.u., other DGs change from the droop mode to the PQ mode while they reach to their permitted ranges for 1 p.u. and they operate in the permitted ranges for 1.02 p.u. Comparing with conventional power flow algorithms, due to the sensitivity problem, the proposed algorithm does not consider any PV bus. Therefore, voltage and frequency of the power system are calculated in the permitted ranges, so that the power mismatch is minimized.

Cases 1 and 2 provide support for the validation of the proposed power flow algorithm. The results show that the proposed algorithm minimizes the power mismatch (see Table 6) by calculating appropriate values for voltage and frequency deviation of droop buses (see Tables 3 and 7). To control the voltage and frequency of power systems and the share of power among DGs, the proper setting of droop coefficients of DGs is vital. In the proposed algorithm, maximum permitted deviation of voltage and frequency is used to set the values of droop coefficient of DGs. See Equations (10) and (11) with the values given in Tables 2 and 4.

Table.7.
Voltage and load profile of a 33-bus microgrid

Bus	Voltage (p.u. ,degree)		Load (p.u.)		Bus	Voltage (p.u. ,degree)		Load (p.u.)	
	V	δ	P_{load}	Q_{load}		V	δ	P_{load}	Q_{load}
2	0.998	0.000	0.1001	0.059	18	0.972	-0.470	0.085	0.037
3	0.998	0.016	0.0901	0.039	19	1.001	0.013	0.090	0.040
4	0.999	0.043	0.1201	0.078	20	1.005	0.118	0.091	0.040
5	1.001	0.069	0.0601	0.030	21	1.007	0.172	0.092	0.040
6	1.003	0.174	0.0603	0.021	22	1.012	0.304	0.091	0.040
7	1.002	0.031	0.2006	0.101	23	0.997	-0.016	0.089	0.049
8	0.995	-0.119	0.1987	0.099	24	0.995	-0.089	0.417	0.198
9	0.994	-0.195	0.0592	0.019	25	0.997	-0.121	0.418	0.198
10	0.987	-0.240	0.0586	0.019	26	1.005	0.198	0.060	0.025
11	0.986	-0.233	0.0444	0.029	27	1.002	0.252	0.060	0.025
12	0.985	-0.221	0.0583	0.034	28	0.992	0.345	0.059	0.019
13	0.979	-0.289	0.0577	0.033	29	0.984	0.429	0.117	0.068
14	0.977	-0.353	0.1162	0.077	30	0.981	0.529	0.195	0.585
15	0.976	-0.383	0.0575	0.009	31	0.977	0.463	0.144	0.067
16	0.975	-0.401	0.0584	0.019	32	0.976	0.445	0.205	0.097
17	0.973	-0.463	0.0578	0.019	33	0.976	0.439	0.058	0.038

6. Summary and Conclusion

In this paper, a novel load flow algorithm was proposed for solving the load flow analysis problem in an islanded microgrid without any slack bus. The steady state frequency was considered as one of the load flow variables via developing a new formula for load flow equations to model different control modes of DGs, such as Droop, PV and PQ, in an islanded microgrid. ICGA was able to minimize the mismatch of total active and reactive power. ICGA algorithm was proposed to solve proposed load flow algorithm for finding the system frequency and local voltage at each bus of the DG unit based on droop controller. ICGA method has features of each method GA and ICA to find best solution of optimization problem. The performance of the proposed algorithm was evaluated by applying it to 6-bus and 33-bus microgrid systems. The results supported the validity of the proposed algorithm. The results also support the effectiveness of the proposed method compared with ICA and Newton-trust.

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