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Research Paper

Optimal Power Flow Using Adaptive Droop Coefficients and Considering the Probability Approach of Renewable Sources and Load

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Abstract: Fair distribution of generated power has a significant impact on the performance of the power system. Many methods have been proposed for the safe and secure operation of power systems under the uncertainties of distributed generators and system load. In this paper, we present an optimal power distribution algorithm for distributed generators against uncertainties and load changes of direct-current and alternating-current transmission systems. In this optimal algorithm, considering the stable-state constraints for all uncertainties is performed. In order to establish these constraints at the lowest cost, the adaptive droop coefficients are employed to optimize the power sharing, reloading and modifying the power coefficient of each distributed generator in the power system. Simulation results show the efficiency of the proposed method to improve the performance of the system and reduce the total cost. The voltage/power deviation from reference value in the proposed method is about 1-1.5% where in the conventional droop control, it is more than 2-3%. In addition, in the same uncertainty of the load/distributed generator power in the test system, proposed method requires 20% less power redistribution compared to the conventional droop method. Also, total cost increasing (due to uncertainty increasing) in the conventional droop method is higher than the proposed method (about 10-15%) which shows the robustness of the suggested method against uncertainty changes.

Keywords: Adaptive Droop Method, Power Distribution, Probability Model, Uncertainty of Distributed Generators Power, Uncertainty of Load.

1 Introduction

IN many power systems, load and power balance play an important role in the overall stability of the main parameters of the system such as frequency and voltage. Therefore, in many researches, the stable frequency/voltage performance of the system has been studied and many methods have been proposed. On the other hand, due to the uncertainty of power generation in distributed generators (DGs) such as photovoltaic (PV) and wind turbine (WT), different probabilistic approaches are employed to overcome the fluctuations in the power flow due to these uncertainties, which leads to voltage/frequency deviation. In [1], the power dissipation algorithm under variable climatic conditions which affect the generated power of PV and WT is investigated. The real 3-year data is collected in this paper and tested on IEEE 30-bus system. The resistive load distribution based on the uncertainty of power generation is presented in the alternating-current/direct-current (AC/DC) microgrid system in [2]. Balanced power distribution has been focused in this paper considering high uncertainty of DGs power. In [3], the optimal power dissipation method for an islanded microgrid is discussed based on the convex problem and convex constraints using MOSEK and GAMS. It is shown that the performance of the proposed method is not dependent on the topology of the power system. Optimal charge diffusion based on the Newton-Raphson method is presented

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in [4, 5] considering the uncertainty of PV and its effect on the control of charge diffusion. Uncertainty analysis to better control and improve the reliability of the power system is presented in [6, 7]. In [8, 9], the power uncertainty of the WT is considered where the optimal power distribution is focused. 41-bus distribution system is considered on which the proposed method is tested while a nonlinear programming of the coefficients is assumed in the final cost function for the optimization process. In [10], using the Jaya algorithm, the optimization of power distribution is proposed based on minimizing the power generation costs and power loss and improving the voltage stability. IEEE 30-bus test system is considered where the performance of the proposed algorithm is compared with other optimization algorithms. The simulation test is based on the presence or absence of DGs in some buses where the approach of optimal DG placement is concentrated. In [11], Weed optimization algorithm and Powell search algorithm have been implemented for optimal power distribution. The cost function is based on fuel cost reduction and pollution factor minimization. In [12], various optimization methods such as artificial neural network and particle swarm optimization are used for power generation cost reduction and pollution minimization as well as voltage profile improvement. In [13], different methods of power distribution are tested in microgrid including different DGs. The effect of the flexible AC transmission (FACT) devices on the optimal power distribution using the particle swarm optimization is stated in [14] where the test system is IEEE 30-bus system. In [15], two types of load model as power-based and pole-zero are presented to discuss the effect of these models on the power distribution. CONOPT solution method in GAMS has been used to solve the problem of power dissipation optimization in [16]. In [17], Locomotive optimization method is used to optimize the cost function based on fuel costs, pollution and losses which has been tested in IEEE 30-bus system. Ant-milk optimization algorithm is applied in [18] to solve the optimal power dissipation problem. Applying the renewable DGs such as WT and PV and optimal placement of them is discussed in [19] where their effects on the voltage stability and system cost is also analyzed. Considering the effect of energy storage on the performance of the microgrid is discussed in [20, 21]. The optimization is done by particle swarm optimization. Squirrel-cage search algorithm and Wall optimization algorithm are combined in [22-24] to optimize the load distribution in the microgrid with the assumption of energy exchange between load and DGs. In [25], intelligent optimal power flow controller based on Grasshopper optimization algorithm is proposed. Harmonic distortion and voltage deviation are minimized to improve the power quality of the grid-connected microgrid. The problem of optimized control of power flow under energy constraints has been discussed in [26] where islanded and grid-connected modes have been studied. The existence of non-linear constraints in optimal power flow problem is focused in [27] where second-order cone relaxation method is suggested to realize linear transformation. Optimal approach based on cost minimization and model of electricity-gas integrated energy is stated in this paper. Forecasting renewable energy is a solution for more reliability of the power system, which is proposed in [28]. Forecasting–based, day-ahead dynamic optimal power flow is presented with the forecasting of PV/WT using artificial neural networks. Moreover, IEEE 30-bus transmission network has been used where Newton-Raphson technique is used for load flow analysis.

In this paper, the optimal power distribution based on the adaptive droop coefficients is applied. Using adaptive droop method helps the system to redistribute the power variations to achieve the balanced state. Due to the robustness of the proposed method, redistribution occurs in more uncertainty rather than conventional droop method which leads to total cost reduction. Moreover, the uncertainty is modeled using probabilistic approach where in existence of the proposed method, the optimal power flow is done even in severe change and uncertainties of load and DGs power. Three types of uncertainties as norm 1, norm 2 and infinite norm are assumed and the analysis of the control system performance is discussed in details. Thus, the main novelties of the paper can be summarized as follow:

- Adaptive droop coefficient approach for balanced power flow
- Uncertainty modeling of load and distributed generator power for more robust control of frequency and voltage
- Three different types of uncertainty (norm 1, norm 2 and infinite norm) consideration and analysis of the performance of the system using conventional and adaptive droop methods
- Analysis of power redistribution in the power system when uncertainty variation occurs
- Power/voltage profile analysis using the proposed adaptive droop and conventional droop methods

The rest of the paper is organized as follow. In Section 2, the main problem is stated where in Section 3, the proposed method formulation is presented. In Section 4, the test and simulation results of the proposed method and comparison with conventional droop method are stated where in the last section, Section 5, some conclusions and future works are presented.

2 Problem Statement

Fig. 1 shows the global topology of the proposed system. In this figure, v_i and p_i are the voltage and injected power of i-th bus, respectively. For each line i-j, y_{ij} indicates the admittance of that line. In the assumed microgrid, y_{ij}, p_i, v_i are real numbers and

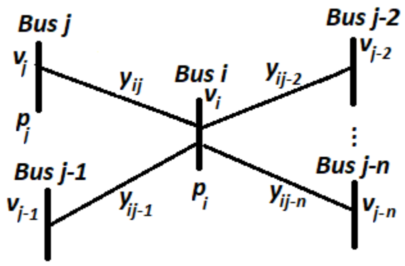

Fig. 1 Topology of the proposed power system.

$y_{ij} > 0$. In this figure, transmission regulators based on the droop method are used to maintain the system in stable state at the lowest cost despite the uncertainty of renewable DGs and variable loads. In fact, the regulator does this control by the adjustment of droop coefficients in the presence of variable DGs at the certain times. These coefficients are time-variable and adaptive where this property leads to the selection of the optimal mode to reduce the total system cost and provide optimal power flow. For the optimization process, the AC and DC parts of the system are firstly modeled. Then, these models are combined with an appropriate uncertainty model to be optimized considering the adaptive droop coefficients and power system constraints. Therefore, the problem of optimizing the power distribution of the microgrid based on reducing the cost of the power generation function can be described as follow [12]:

$$\begin{aligned}&\text{prob1:}\\&\min\ h(p)=\sum_{i\in N} f_i(p_i)\\&\text{s.t.:}\\&p_i=\sum\left[v_i\left(v_i-v_j\right)\right]/z_{ij};\quad i,j\in N\\&p_{i.\min}<p_i<p_{i.\max};\quad i\in N\\&v_{i.\min}<v_i<v_{i.\max};\quad i\in N\end{aligned}\tag{1}$$

$f_i(p_i)$ represents the function of power generation costs and power losses (in buses with no DG) in each bus of the set N-bus and $h(p)$ is the function of the total power cost. The power cost function can be represented as below [12]:

$$\begin{cases}f_1(m)=cost_t^p\, p_i^m \gamma_i^m\\ f_2(m)=cost_t^p\, p_{Loss}^m\\ f_3(m)=cost_t^p\, p_{base}^m\\ f_4(m)=cost_t^Q\, Q_{base}^m\end{cases}\tag{2}$$

The first sentence is related to the cost of the power generation capacity, the second sentence is related to the power loss cost and the third and fourth sentences are related to the active and reactive power cost in the base bus of the system, respectively. γ is the efficiency of power generation in the system. Loss power can be written as [12]:

$$p_{Loss}=\sum_{i=1}^{N}\sum_{j=1,i\neq j}^{N}\frac{G_{ij}}{2}\left[\left|v_i\right|^2+\left|v_j\right|^2-2\left|v_i\right|\left|v_j\right|\cos\left(\theta_i-\theta_j\right)\right]\tag{3}$$

where G_{ij} is the real part of admittance of i-j line. According to the above equations, the purpose of the problem is to minimize the power cost function including power generation, losses, active and reactive power in the base bus. Power cost function can be considered as a linear function in the form of $f_i(p_i) = a_i p_i + b_i$ in which a_i and b_i are the linear cost coefficients. In this approach, the solution of the optimization problem can be modeled in a simpler form where the load distribution can be changed and written as follow [12, 2]:

$$\begin{cases}p_i=\dfrac{\sum\left(v_i^2-v_iv_j\right)}{z_{ij}}=\dfrac{\sum\left(A_i-B_{ij}\right)}{z_{ij}};\quad i,j\in N\\ p_{i.min}<p_i<p_{i.max};\quad i\in N\\ v_{i.min}^2<v_i^{\ 2}=A_i<v_{i.max}^2;\quad i\in N\\ v_iv_j=B_{ij}\geq 0;\quad i,j\in N\\ B_{ij}=B_{ji};\quad i,j\in N\end{cases}\tag{4}$$

In which, the square of the bus voltage is denoted by A and the product of the voltage of the two buses is represented with B. In view of apparent power, the equations can be described as [12, 2]:

$$\frac{S_i}{V_i}=\sum_{k=1}^{N}Y_{ik}V_k\tag{5}$$

For the slack bus, it can be written as:

$$V_i(0)=1;\quad i\in bus_{slack}\tag{6}$$

where in the P-Q buses, we have:

$$\sum_{k=0}^{N}Y_{ik}V_k(0)=0;\quad i\in bus_{P-Q}\tag{7}$$

and for P-V buses, it can be written as:

$$\sum_{k=0}^{N}Y_{ik}V_k(0)=\frac{-jQ_i(0)}{V_i(0)};\quad i\in bus_{P-V}\tag{8}$$

Also, in P-V buses, below equation can be mentioned as:

$$V_i(0)\times V_i^*(0)=1;\quad i\in bus_{P-V}\tag{9}$$

In linear-form description of voltage, polynomial-based function can be assumed as [12, 23]:

$$V(q)=\sum_{i=0}^{N}V(i)q^i=V(0)+V(1)q+\ldots+V(N)q^N\tag{10}$$

where in Taylor-based expansion of the voltage of different buses, we have [12, 23]:

$$\sum_{k=1}^{N} Y_{ik.series}\left(V_k(0)+V_k(1)q+\ldots+V_k(N)q^N\right) = \left[\frac{S_i}{\left(V_i(0)+V_i(1)q+\ldots+V_i(N)q^n\right)} - Y_{i.shunt}V_i\left(V_i(0)+V_i(1)q+\ldots+V_i(N)q^n\right)\right]; \quad i\in bus_{P-V} \tag{11}$$

Using the auxiliary variable of voltage, it is assumed as:

$$U(q)=\frac{1}{V(q)}=U(0)+U(1)q+\ldots+U(N)s^n \tag{12}$$

Thus, we have:

$$\begin{cases} U(0)=\dfrac{1}{V(0)}; & \text{for } i=0 \\ U(i)=\dfrac{-\sum_{\delta=0}^{n}U(\delta)V(i-\delta)}{V_i(0)}; & \text{for } i\geq 0 \end{cases} \tag{13}$$

and

$$\sum_{k=1}^{N} Y_{ik}V_k(i)=S_iU(i-1)-Y_{i,shunt}V(i-1) \tag{14}$$

For the active power in P-V buses, we have [12, 23]:

$$P_i=\mathrm{Re}\left(V_i\sum_{k=1}^{N}Y_{i,k}V_k\right); \quad i\in bus_{P-V} \tag{15}$$

$$\sum_{k=1}^{N} Y_{ik.series}V_k(q)=\frac{P_i-jQ_i(q)}{V_i(q)} - Y_{i.shunt}V_i(q); \; i\in bus_{P-V} \tag{16}$$

Due to considering the uncertainties in the microgrid, the probabilistic models must be assumed for load and DGs power change. Therefore, probability function of load is considered as normal distribution [7, 23]:

$$f_{load}(x)=\frac{1}{\sigma_{load}\sqrt{2\pi}}\exp\left(\frac{-\left(x-\mu_{load}\right)^2}{2\sigma_{load}^2}\right) \tag{17}$$

and for the WT, we have Weibull distribution as [7, 23]:

$$f_{WT}(x)=\left(\frac{K}{c}\right)\left(\frac{x}{c}\right)^{K-1}\exp\left(-\left(\frac{x}{c}\right)\right)^{K}; \quad 0<x<\infty \tag{18}$$

where K and c are the constants in this function and the generated power can be approximated as below:

$$P_{WT}=\begin{cases} 0; & \text{for } V<V_{cut-in} \\ 0.5\rho A_{wt}C_p(\beta,\lambda)V_W^3; & \text{for } V_{cut-in}\leq V\leq V_r \\ P_r; & \text{for } V_r\leq V\leq V_{cut-out} \\ 0; & \text{for } V>V_{cut-out} \end{cases} \tag{19}$$

$V_{cut\text{-}in}$ and $V_{cut\text{-}out}$ are the wind velocity in lower and upper bound, respectively and V_r is the rated wind velocity. Also, moment method can be applied for the modeling of the probabilistic approach as:

$$M_X(t)=\int_{-\infty}^{+\infty}e^{tx}f_x(x)dx \tag{20}$$

3 Proposed Method

The power system model consists of two parts, AC and DC. The interface converters are responsible for converting these two parts to each other which can be modeled as current or voltage sources. To distribute power from the DC part to the AC part, positive direction is assumed as $P_{DC,AC}$ > 0. The power flow model is based on the droop equation in the converter as follow [12, 2]:

$$P=P_{t_0}+L_V\Delta V+L_P\Delta f \tag{21}$$

The voltage and frequency droop coefficients are denoted by L_V and L_P. The reference power is P_{t0} in the system where the power is varied due to the frequency and voltage droop coefficients. For DC/DC converters in the power system, the nominal voltages in the primary and secondary parts exist, which can be used in the active power regulation for the converter as [5]:

$$P=P_{t_0}+L_{V1}\Delta V_1+L_{V2}\Delta V_2 \tag{22}$$

Thus, according to equations (21) and (22), voltage and frequency changes can be adjusted due to the active power in AC and DC converters. Equations (21) and (22) can be written in matrix form as [12, 5]:

$$\begin{cases} \Delta P_{AC}=L_V\Delta V+L_P\Delta f \\ \Delta P_{DC}=L_V\Delta V \end{cases} \tag{23}$$

Matrix-based equations are considered for all buses where frequency/voltage adjustment is done in buses with the power change. In the proposed problem, the redistribution of the power must be done to achieve the balanced power flow in the system. Thus, if the generated power of some DGs decreases, the generated power of some other DGs must be increased to compensate the power reduction. In fact, the balance of power generation can be described as:

$$P_{G1}+P_{G2}+P_{G3}+\ldots=P_t \tag{24}$$

which shows that the total power capacity has an upper bound (P_t) for limiting the power cost.

3.1 AC and DC Constraints

3.1.1 AC Constraints

1) The first AC constraint is as [12, 5]:

$$L_P^{-1}\left(\Delta P - L_V \Delta V\right) \leq \overline{\Delta f} \tag{25}$$

which indicates that the frequency changes must be less than the preset average ($\overline{\Delta f}$).
2) The limit of the active power of the DGs is as follow:

$$P_{\min} \leq P_{AC} \leq P_{\max} \tag{26}$$

3) The power which flows through the transmission line is directly proportional to the difference in voltage angle of the line, i.e.:

$$P_{ij} \propto \Delta\theta_{ij} \tag{27}$$

$\Delta\theta_{ij}$ is the voltage phase of line *i*-*j*.

3.1.2 DC Constraints

1) The first DC constraint can be described as [12, 5]:

$$\left(V_m - V_n\right) \leq \Delta V \tag{28}$$

V_m is the deviated voltage due to uncertainty in load/DG power change, and V_n is the DC reference voltage of the microgrid where the maximum variation must be limited due to this constraint.
2) The limit of the active power of the converter is as follow, which indicates the upper power bound.

$$\left|P_C\right| \leq P_{C.\max} \tag{29}$$

3) Uncertainty limit is described as the normalized summation (S_m) of the uncertainty vector including the uncertainty of the power generation and load of the system which must be limited as below [12, 23]:

$$S_m = \sum_{n=1}^{U}\left(\left|\frac{\Delta S_n}{\Delta S_n^{''}}\right|^m\right)^{\frac{1}{m}} \leq 1 \tag{30}$$

where S is inside the convex set, S_m. U is also the set of uncertainties in the system where the above equation guarantees the stability of the system, because if there is more uncertainty in the system, voltage and frequency instability will occur.

3.2 Branch Distribution Model

According to (4) and (16), A_i and B_{ij} may be numerically very close to each other, because the node voltage range is small (usually 0.95 to 1.05 p.u.). The power distribution with conversion of Prob1 (Eq. (1)) to the branch distribution model is described as [12, 2]:

$$u = \begin{cases} A_i' = A_i \\ k_{ij} = \left(A_i - B_{ij}\right) y_{ij} \\ c_{ij} = y_{ij}^2\left(A_i - B_{ij} - B_{ij} + A_j\right) \end{cases} \tag{31}$$

where k and c are the branch power distribution and squared branch current, respectively. Based on (31) and using load distribution of model u, the optimal load distribution problem can be presented as:

$$\begin{aligned}
&\text{prob2:}\\
&\min \ h(p)\\
&\text{s.t.:}\\
&K_i = \sum_{j:j\sim i} k_{ij}; \quad i \in N\\
&k_{i.min} \leq k_i \leq k_{i.max}; \quad i \in N\\
&v_{i.min}^2 < A_i' < v_{i.max}^2; \quad i \in N\\
&k_{ij} + k_{ji} = z_{ij} c_{ij}; \quad i, j \in N\\
&A_i' - A_j' = z_{ij}\left(k_{ij} - k_{ji}\right); \quad i, j \in N\\
&c_{ij} = k_{ij}^2 / A_i; \quad i, j \in N
\end{aligned} \tag{32}$$

where $z_{ij} = 1/y_{ij}$. In the sequel of the paper, optimization is done in the test system including DGs, converters and loads where uncertainty in loads and renewable DGs is considered. Optimizing of the defined problem (prob2) based on the balanced power distribution is performed using frequency and voltage droop coefficients and considering the constraints. The final goal is to achieve the optimal load or power distribution by applying the optimal adaptive droop coefficients. If uncertainty causes the stable point deviation, power redistribution is formed using adaptive droop coefficients, which leads to cost and loss reduction. Here, the linear-form power distribution model mentioned in (1), (16), and (32) is focused where efficient Opti toolbar in MATLAB is used for the optimization process.

4 Simulation Results

To test the proposed method, the small power system consisting of two AC networks is considered and shown in Fig. 2. Two AC networks are connected to each other via DC/AC converter. A scenario is defined as 800 MW load is connected to bus 4 and three DGs are connected to buses 2, 3, and 5 where the connected lines with the capacity of 200 MW exist in the network. It is assumed that the connected DG to bus 2 can have an energy storage element while the DG in bus 3 cannot provide any storage. The goal is to minimize the cost of load redistribution and consequently the cost of the entire system under load uncertainty in bus 4. DC/AC converters are equipped with droop controllers and the load uncertainty of less than 70 MW is assumed. For load uncertainty higher than 70 MW, power lines between buses (1, 4) and (2, 4) are overloaded (due to

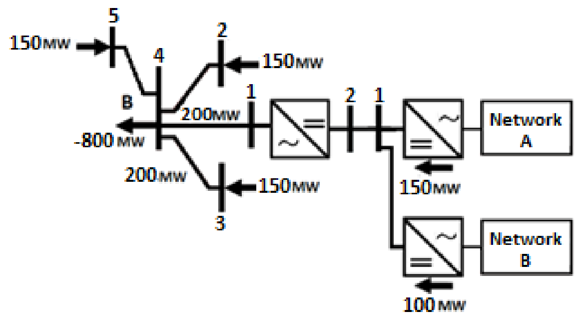

Fig. 2 Small test system for the proposed optimization problem.

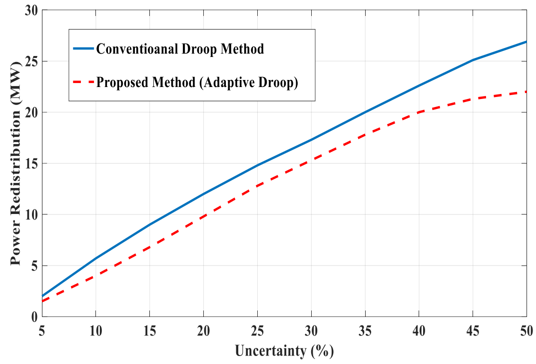

Fig. 3 Minimum redistribution required as a function of load uncertainty in bus 4 for the test system of Fig. 2.

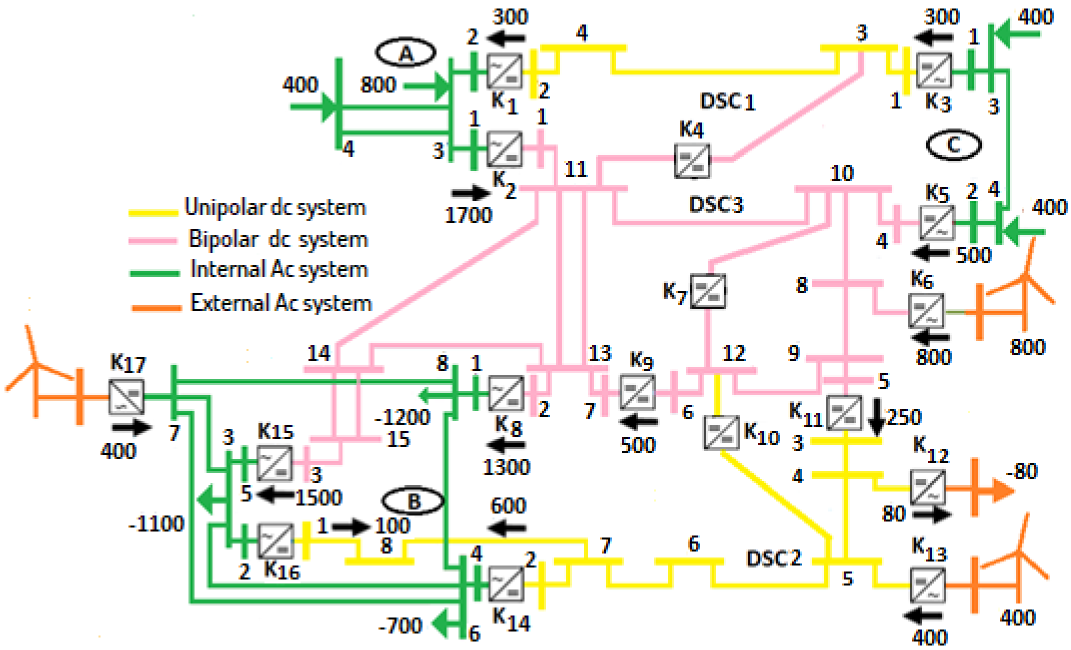

Fig. 4 Complex test system including uncertainty in load and DGs.

capacity bound of 35 MW for each line) and thus, redistribution is not prevented. Fig. 3 shows the dependence of the optimization results on the load uncertainty. Therefore, the optimization is done again to achieve the new stable point with increasing uncertainty. As can be seen from the figure, in the proposed method with adaptive droop coefficients, with increasing uncertainty, the redistributed power is less than the case of conventional droop coefficients (with no adaptive adjustment). Moreover, as can be seen in this figure, if the system load has more uncertainty than the specified value, the minimum number of power redistribution is increased, which means the main increase in system cost.

More complex test system is assumed in Fig. 4, which consists of three AC sections and three DC sections. Converters 6, 12, 13, and 17 are connected to WT and loads. Converters 2, 3, 8, and 16 only control the DC voltage used for adjusting the power distribution. Also, the converters 1, 5, 14, and 15 control the active power distribution depending on the AC frequency and DC voltage. The uncertainty is assumed in two locations of the network: bus 6 in part B and bus 5 in DSC2. Each of these buses has 150 MW uncertainty. When the load on the bus 6 of part B increases by 150 MW, the frequency of the part B is decreased by 0.25 Hz. In addition, if WT output is increased by 150 MW at DSC2 of bus 5, the frequency will decrease by 0.25 Hz.

The initial droop coefficients are presented in Table 1. Initial coefficients cannot guarantee the optimal control of frequency and voltage during changes in load and DGs power and thus, the cost of the system will increase. Adaptive droop coefficients based on optimization process and constraints are proposed in Table 2 to reduce the total cost of the system. Due to the control process, the initial storage in sections A and C is directed to part B where the power flow is done through K_8 and K_{15} between bus 5 and 6 in DCS2. Also, in case of additional power generation of WT in bus 5, DSC2 may be degraded in power balance. Therefore, the voltage and frequency coefficients in this bus must be adapted to these changes.

Table 1 Initial voltage and frequency droop coefficients.

	K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8
L_V	17.20	19.10	19.15	4.20	19	5.40	5.20	5.40
L_P	0.3	6.5	7.4	18.77	13.8	19.2	19.17	19.05
	K_9	K_{10}	K_{11}	K_{12}	K_{13}	K_{14}	K_{15}	K_{16}
L_V	5.28	6.02	11.93	12.11	0.87	0.85	4.8	0.34
L_P	19.03	17.9	5.9	10.4	11.02	10.5	18.5	17.8

Table 2 Optimal droop coefficients in different parts of the system.

	AC Part			
	A		C	
	Bus 3	Bus 4	Bus 3	Bus 4
L_P	19	19.15	9.3	19.1

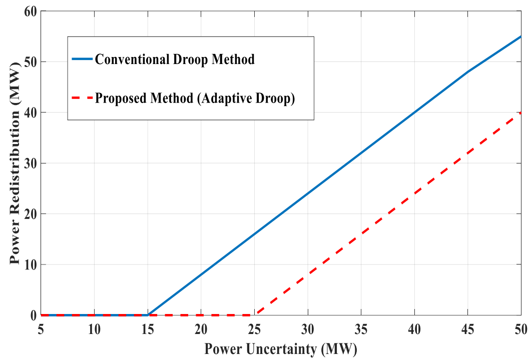

Fig. 5 Power redistribution in proposed method compared to initial droop coefficients.

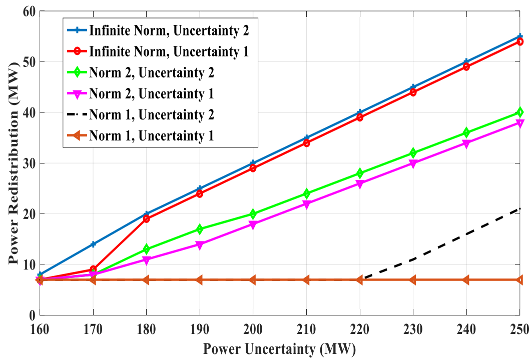

Fig. 6 Power redistribution in terms of different uncertainty scenarios, infinity, norm 1 and norm 2.

To demonstrate the efficiency of the proposed method in the higher uncertainty ranges, the generated power between bus 5 and 6 at DSC2 is reduced for redistribution of power in the system. Fig. 5 shows that with the proposed method, the required redistribution is minimized, while with the initial droop parameters, redistribution results in the high cost on the system. According to this figure, using the initial parameters, redistribution starts from uncertainty of 15 MW, but using the proposed method, power redistribution starts from uncertainty of 25 MW which indicates the reliability and robustness of the system by applying the proposed method. Indeed, this figure shows the robustness of the proposed method in high uncertainty of the system.

In the following, three types of uncertainties are assumed in the system to analyze the robustness of the proposed model in different uncertainty values. In the first scenario, it is assumed that all uncertainties are independent from each other (infinite norm). In the second hypothetical type, the uncertainties are interrelated, and in fact, there is a conditional probabilistic relationship between these uncertainties known as norm uncertainty (norm 1). In the third type, a combination of infinite norm and norm 1 is considered as uncertainty norm 2. Fig. 6 shows the result of power redistribution in these uncertainties. It can be seen that if infinite norm is considered, the most power redistribution in the system is required, while the lowest cost is obtained in the case of the dependence of uncertainties (norm 1). In norm 1, dependent uncertainties cause simpler analysis for power redistribution and adaptive droop coefficients. In this figure, the uncertainties are considered in bus 6 of part B and bus 5 in DSC2. Fig. 6 also shows the advantage of the proposed approach compared to initial droop coefficients where the proposed method significantly reduces redistribution costs by optimizing the droop coefficients.

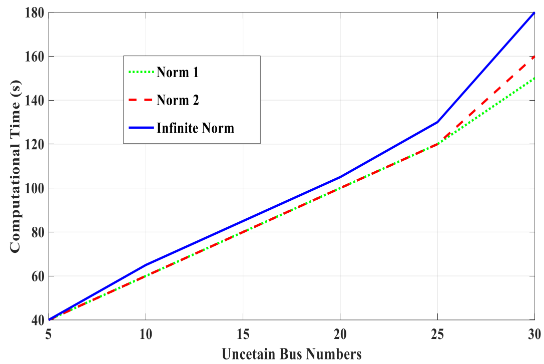

Fig. 7 Computational time of power redistribution in different uncertainty scenarios.

The required computational time is depicted in Fig. 7 for the power redistribution of proposed method in three uncertainty scenarios. As can be seen, the computational time for norm 1 is less than other two scenarios. In addition, the computational time in norm 1 and norm 2 is linearly dependent on the uncertainty value where in infinite norm, it is not linear. If the uncertainty is increased, more time is needed to solve the optimal power distribution and redistribution. Also, as the number of uncertainties increases, the set of constraints becomes more limited and thus, the convergence occurs with more time delay.

Fig. 8 shows the result of the required redistribution in term of average uncertainty in the test system. As can be seen, the proposed method needs less power redistribution compared to the conventional droop method. Thus, the total cost is reduced in the proposed strategy compared to the conventional droop control. Norm 1 uncertainty is assumed in this simulation.

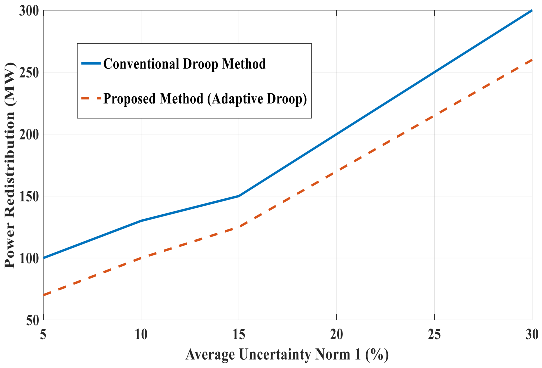

Fig. 8 Required power redistribution versus average norm 1 uncertainty.

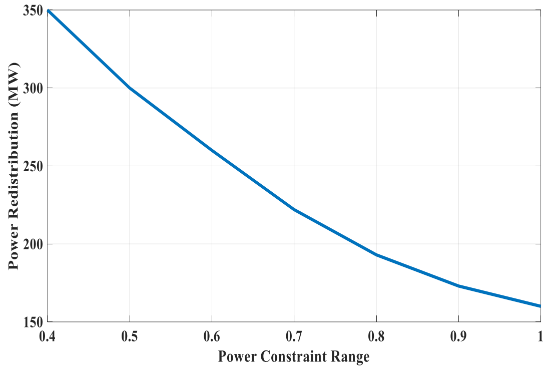

Fig. 9 Power redistribution of the proposed method by increasing the power constraint of DGs and loads.

Table 3 Voltage, active and reactive power of sample buses of the system in proposed method and conventional droop method.

Bus	Proposed method voltage (V)	Proposed method active power (P)	Proposed method reactive power (Q)	Conventional droop method voltage (V)	Conventional droop method active power (P)	Conventional droop method reactive power (Q)
4 (DSC1)	1.01 (1%)	1.03 (1.5%)	1.02 (1.5%)	1.03 (2%)	1.045 (3%)	1.05 (3%)
6 (DSC2)	1.015 (1%)	1.02 (1.5%)	1.02 (1.5%)	1.04 (2%)	1.05 (3%)	1.06 (3%)
10 (DSC3)	1.02 (1%)	1.03 (1.5%)	1.03 (1.5%)	1.05 (2%)	1.05 (3%)	1.055 (3%)
2 (DSC4)	1.03 (1%)	1.025 (1.5%)	1.03 (1.5%)	1.06 (2%)	1.04 (3%)	1.065 (3%)

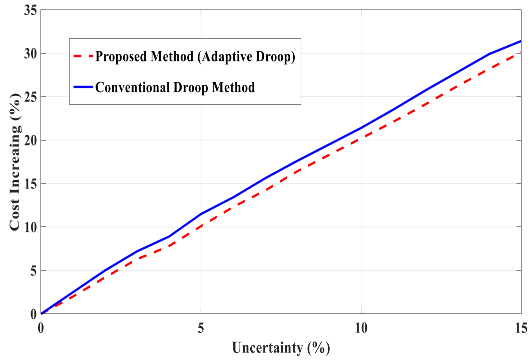

Fig. 10 Cost increasing versus uncertainty increasing using proposed method and conventional droop method.

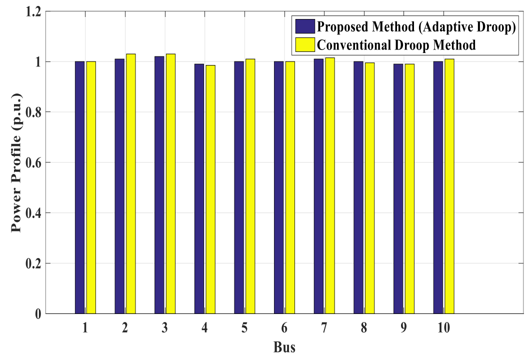

Fig. 11 Power profile in proposed method and conventional droop method.

Fig. 9 shows the required power redistribution in term of the constraints range in DGs and load power. As can be seen, more constraints cause more power redistribution because of more limitation imposed on the system performance. Thus, more time is needed for the convergence which leads to the total cost increasing.

In the next test, the voltage, active power and reactive power of several sample buses in conventional droop method and proposed method are described in Table 3. The deviation percent from reference value is denoted in parenthesis. As can be seen, the stability of voltage, active and reactive power using the proposed method is more than the case of using the conventional droop method. Thus, the proposed strategy can help the system to maintain the stability conditions where it is more robust to the parameter variations compared to the conventional droop method.

The effect of the proposed approach on the total cost of the system considering the uncertainty variation is depicted in Fig. 10. As can be seen, the cost increasing in proposed method is less than the conventional droop method where the uncertainties are increased in the power system. In addition, the power profile of two methods is compared in Fig. 11. As observable, the stability of the power profile using the proposed method is better than conventional method which verifies the robustness of the power distribution in the proposed approach.

The limitation of the proposed model is more convergence time related to the conventional droop method where in view of efficiency and improvement of the system, the proposed method is much better than conventional droop method which can be observed form the results. The suggested method can be used in many power systems with renewable DGs and variable loads which provides the stable frequency/voltage and optimal balanced power flow.

5 Conclusion

In this paper, adaptive droop approach is proposed for stable power flow, frequency/voltage regulation and interesting power redistribution in various uncertainties of power of DGs and loads. Adaptive droop coefficient helps the system to optimally distribute the power to prevent the overload. The total cost is also reduced using the proposed method compared to the conventional droop method as shown in simulation results. In addition, using adaptive droop coefficients, the performance of the power system in various types of uncertainties as norm 1, norm 2 and infinite norm is improved with 20% more robustness in power redistribution compared to the conventional droop method. Moreover, voltage/power deviation from reference value is about 1-1.5% using the proposed method which is less than deviations in conventional droop method.

For the future works, the proposed method can be tested on the islanded microgrid and the results are compared to this paper. Frequency and voltage deviations can be the main challenges in these results. Also, evolutionary algorithms can be combined with the proposed adaptive droop method to evaluate the efficiency of the proposed method in both islanded and grid-connected modes.

Intellectual Property

The authors confirm that they have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property.

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Declaration of Competing Interest

The authors hereby confirm that the submitted manuscript is an original work and has not been published so far, is not under consideration for publication by any other journal and will not be submitted to any other journal until the decision will be made by this journal. All authors have approved the manuscript and agree with its submission to "Iranian Journal of Electrical and Electronic Engineering".

References

[1] A. Ahmed, F. J. S. McFadden, and R. Rayudu, "Weather-dependent power flow algorithm for accurate power system analysis under variable weather conditions," *IEEE Transactions on Power Systems*, Vol. 34, No. 4, pp. 2719–2729, Jul. 2019.

[2] A. Mešanović, U. Münz, and C. Ebenbauer, "Robust optimal power flow for mixed AC/DC transmission systems with volatile renewables," *IEEE Transactions on Power Systems*, Vol. 33, No. 5, pp. 5171–5182, Sep. 2018.

[3] J. Li, F. Liu, Z. Wang, S. H. Low, and S. Mei, "Optimal power flow in stand-alone DC microgrids," *IEEE Transactions on Power Systems*, Vol. 33, No. 5, pp. 5496–5506, Sep. 2018.

[4] Y. B Wang, C. S. Wu, H. Liao, and H. H. Xu, "Steady-state model and power flow analysis of grid-connected photovoltaic power system," in *IEEE International Conference on Industrial Technology*, Chengdu, pp. 1–6, 2008.

[5] A. Ketabi, S. Rajamand, and M. Shahidehpour, "Power sharing inparallel inverters with different types of loads," *IET Generation, Transmission and Distribution*, Vol. 11, No. 10, pp. 2438–2447, 2017.

[6] H. Saboori and S. Jadid, "Optimal scheduling of mobile utility-scale battery energy storage systems in electric power distribution networks," *Journal of Energy Storage*, Vol. 31, p. 101615, 2020.

[7] R. Hemmati and H. Saboori, "Stochastic optimal battery storage sizing and scheduling in home energy management systems equipped with solar photovoltaic panels," *Energy and Buildings*, Vol. 152, pp. 290–300, 2017.

[8] E. Mohagheghi, A. Gabash, and P. Li, "A framework for real-time optimal power flow under wind energy penetration," *Energies*, Vol. 10, No. 4, p. 535, 2017.

[9] T. Samakpong, W. Ongsakul, and N. Madhu Manjiparambil, "Optimal power flow incorporating renewable uncertainty related opportunity costs," *Computational Intelligence*; pp. 1–26, Apr. 2020.

[10] M. Ćalasan, T. Konjić, K. Kecojević, and L. Nikitović, "Optimal allocation of static var compensators in electric power systems," *Energies*, Vol. 13, No. 12, p. 3219, 2020.

[11] M. Kaur and N. Narang, "An integrated optimization technique for optimal power flow solution," *Soft Computing*, Vol. 24, pp. 10865–10882, 2020.

[12] M. Ebeed, S. Kamel, F. Jurado, "Optimal power flow using recent optimization techniques," in *Classical and recent aspects of power system optimization*, Academic Press, pp. 157-183, 2018.

[13] B. Khan and P. Singh, "Optimal power flow techniques under characterization of conventional and renewable energy sources: A comprehensive analysis," *Journal of Engineering*, p. 9539506, Vol. 2017, 2017.

[14] K. M. Metweely, G. A. Morsy, and R. A. Amer, "Optimization of optimal power flow problems with FACTS devices using PSO technique," in *Nineteenth International Middle East Power Systems Conference (MEPCON)*, Cairo, pp. 181–189, 2017.

[15] M. Jereminov, B. Hooi, A. Pandey, H. Song, Ch. Faloutsos, and L. Pileggi, "Impact of load models on power flow optimization," in *IEEE Power & Energy Society General Meeting (PESGM)*, pp. 1–5, 2019.

[16] M. P. Ćalasan, L Nikitović, and S. Mujović, "CONOPT solver embedded in GAMS for optimal power flow," *Journal of Renewable and Sustainable Energy*, Vol. 11, No. 4, p. 046301, 2019.

[17] M. A. Taher, S. Kamel, F. Jurado, and M Ebeed, "Modified grasshopper optimization framework for optimal power flow solution," *Electrical Engineering*, Vol. 101, No. 1, 2019.

[18] O. Herbadji, L. Slimani, and T. Bouktir, "Optimal power flow with four conflicting objective functions using multiobjective ant lion algorithm: A case study of the Algerian electrical network," *Iranian Journal of Electrical and Electronic Engineering*, Vol. 1, No. 1, pp. 94–113, 2019.

[19] U. Khaled, A. M. Eltamaly, and A. Beroual, "Optimal power flow using particle swarm optimization of renewable hybrid distributed generation," *Energies*, Vol. 10, No. 7, p. 1013, 2017.

[20] A. Naderipour, H. Saboori, H. Mehrjerdi, S. Jadid, Z. Abdul-Malek "Sustainable and reliable hybrid AC/DC microgrid planning considering technology choice of equipment," *Sustainable Energy, Grids and Networks*, Vol. 23, p. 100386, 2020.

[21] S. Amiri, S. Jadid, H. Saboori, "Multi-objective optimum charging management of electric vehicles through battery swapping stations," *Energy*, Vol. 165, pp. 549–562, 2018.

[22] M Durairasan and D. Balasubramanian "An efficient control strategy for optimal power flow management from a renewable energy source to a generalized three-phase microgrid system: A hybrid squirrel search algorithm with whale optimization algorithm approach," *Transactions of the Institute of Measurement and Control*, Vol. 42, No. 11, pp. 1960–1976, Feb.2020.

[23] A. Ramadan, M. Ebeed, S. Kamel, L. Nasrat, A. F. Zobaa, and S. H. E. Abdel Aleem, "Optimal power flow for distribution systems with uncertainty," in *Uncertainties in modern power systems*, Academic Press, pp. 145–162, 2021.

[24] A. Arrigo, C. Ordoudis, J. Kazempour, Z. de Grève, J. Toubeau, and F. Vallée, "Optimal power flow under uncertainty: An extensive out-of-sample analysis," in *IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*, Bucharest, Romania, pp. 1–5, 2019.

[25] Jumani, Touqeer Ahmed and Mustafa, Mohd Wazir and Md Rasid, Madihah and Hussain Mirjat, Nayyar and Hussain Baloch, Mazhar and Salisu, Sani, "Optimal power flow controller for grid-connected microgrids using grasshopper optimization algorithm," *Electronics*, Vol. 8, No. 1, p. 111, 2019.

[26] I. Ghenea, M. Gaiceanu, and R. Buhosu, "Microgrid optimal power flow for increased security," in *6th International Symposium on Electrical and Electronics Engineering (ISEEE)*, pp. 1–6, 2019.

[27] F. Zhang, Zh. Shen, W. Xu, G. Wang, B. Yi, "Optimal power flow algorithm based on second-order cone relaxation method for electricity-gas integrated energy microgrid," *Complexity, Advanced Control and Optimization for Complex Energy Systems*, 2021.

[28] M. A. Ilyas, Th. Alquthami, M. Awais, A. H. Milyani, and M. B. Rasheed, "(DA-DOPF): A day-ahead dynamic optimal power flow with renewable energy integration in smart grids," *Frontiers in Energy Research*, Vol. 9, pp. 424, 2021.

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