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A Novel Multi-objective Optimization Dispatch Model for Hybrid Thermal-Wind-PV Power System

***Abstract**. A novel multi-objective model for hybrid thermal-wind-PV power system is proposed in this paper to solve the problem of energy saving and emission reduction/economic dispatch which is optimized by proposed Karush-Kuhn-Tucker (KKT) and quantum genetic algorithm (QGA). Through detailed analyses, mathematical functions of power operation, energy consumption and emission and relevant constraint conditions are proposed, and then for the first time, the multi-objective optimization model of energy saving and emission reduction/economic dispatch including thermal power, wind power and PV power is established. KKT is used to transform multi-objective model into single-objective one, QGA is used to optimize the single-objective model, then a novel KKT and QGA is proposed. Several simulations including wind power, PV power and thermal power are proposed, which shows positive effects of wind power and PV power in energy saving and emission reduction. The experimental study shows that the proposed algorithm is more accurate and with less computational time than commonly used optimization methods. The actual implementation results prove that the model and algorithm are effective and practical to reduce power cost, energy consumption and emission.*

***Streszczenie.** W artykule przedstawiono model hybrydowego systemu Odnawianych Źródeł Energii (termiczne, wiatrowe, fotowoltaika). W modelu wzięto pod uwagę optymalizację użytkowania (oszczędzanie energii oraz ekonomika wytwarzania). Wykorzystano metodę Karush-Kuhn-Tucker oraz QGA. Na podstawie analiz, opracowano funkcje matematyczne dotyczących przesyłu, emisji i zużycia energii oraz ograniczeń z nimi związanych. Wyniki badań symulacyjnych i eksperymentalnych potwierdzają skuteczność działania zaproponowanej optymalizacji (M**odel optymalizacji wielokryterialnej na potrzeby hybrydowego termiczno-wiatrowo-PV systemu Odnawialnych Źródeł Energii**).*

Keywords: multi-objective optimization, Karush-Kuhn-Tucker, quantum genetic algorithm, hybrid power system.
Słowa kluczowe: optymalizacja wielokryterialna, Karush-Kuhn-Tucker, QGA, hybrydowy system energetyczny.

Introduction

Wind power and PV power are attaching increasingly attention as clean energy with proposing of energy conservation and emission reduction. Because of the randomness and instability of wind power and PV power[1], literatures [2] studied hybrid PV/Wind Power System including power cost and power risk. However, fewer literatures have studied joint dispatch model including wind power, PV power and thermal power. Different techniques have been reported in the literatures concerning to the dispatch problem [3]. However they have disadvantages of computationally involved and time-consuming or exist certain dispute and difficult in weight distribution. Based on characteristics of multi-objective optimization and advantages of intelligent algorithms, the KKT algorithm [4] and QGA [5] are combined.

Modeling of multi-objective optimization dispatch

Based on the characteristics of thermal, wind power and PV power generation, the multi-objective energy saving and emission reduction/economic dispatch function is established. The maximal economic benefit equals to minimal power operation cost. Power operation function is expressed by a quadratic equation:

$$f_1 = \sum_{t=1}^{T} \sum_{i=1}^{Ng} a_i P_i^2(t) + b_i P_i(t) + c_i \tag{1}$$

Where Ng is the total number of thermal units in a system; $Pi(t)$ for the real power output of the i^{th} generator in time t; T is the time of one day; a_i, b_i, c_i represent the coefficients of the economic benefit function. Journally the proposed approach for modeling energy saving and emission reduction function is to use a combination of the polynomial and exponential terms for each generating unit:

$$f_2 = \sum_{t=1}^{T} \sum_{i=1}^{Ng} \alpha_i + \beta_i P_i(t) + \gamma_i P_i^2(t) + \xi_i \exp(\omega_i P_i(t)) \tag{2}$$

where $\alpha_i, \beta_i, \gamma_i, \xi_i, \omega_i$ are the emission coefficients of the ith generator. Then the multi-objective model of joint energy saving and emission reduction/economic dispatch are got: $Min(f_1, f_2)$. The relevant **constraint conditions** including power balance, power operation limits, ramp rate limits, spinning reserve are as follows:

$$\sum_{i=1}^{Ng} P_i + P_w + P_v = P_D + P_L \;;\; P_{i\min} \le P_i \le P_{i\max}$$

$$0 \le P_w \le P_{w\max} \,;\; 0 \le P_v \le P_{v\max}$$

$$-R_{idown} \le P_{i(t)} - P_{i(t-1)} \le R_{iup}$$

$$\sum_{i=1}^{Ng} (P_{it\max} \times U_{it}) \ge P_{Dt} + R_{svt} \,.$$

where P_w, P_v are the wind and PV power incorporated in multi-objective optimization dispatch; P_D is the total needed power in corresponding period; P_L is the transmission loss of line which can be calculated based on the Kron's loss formula as follows: $P_L = \sum_{i=1}^{m}\sum_{j=1}^{m} P_i B_{ij} P_j + \sum_{i=1}^{m} B_{0i} P_i + B_{00}$, where B_{ij}, B_{0i}, B_{00} are the transmission network power loss B-coefficients. $P_{i\min}$, $P_{i\max}$ are lower and upper limits of real power output for the i^{th} thermal unit, respectively; $P_{w\max}$ is the upper limit of real wind power output; $P_{v\max}$ is the upper limit of real wind power output. R_{idown}, R_{iup} are the ramp rates for the i^{th} thermal unit, respectively. R_{svt} is the spinning reserved in the t^{th} hour; U_{it}: the ON and OFF status of the i^{th} conventional unit at the t period. (U_{it}=0 represents OFF status, U_{it}=1 represents ON status.)

KKT-QGA to multi-objective optimization dispatch

For energy saving and emission reduction/economic dispatch, as the sub-object, energy saving and emission reduction model is changed firstly by KKT frame.

$$Min \sum_{t=1}^{T} \sum_{i=1}^{Ng} \alpha_i + \beta_i P_i(t) + \gamma_i P_i^2(t) + \xi_i \exp(\omega_i P_i(t)) \tag{3}$$

The Lagrangian equation for (3):

$$\begin{aligned} L = {} & \sum_{t=1}^{T} \sum_{i=1}^{Ng} \alpha_i + \beta_i P_i(t) + \gamma_i P_i^2(t) + \xi_i \exp(\omega_i P_i(t)) \\ & + \lambda\Big(\sum_{i=1}^{Ng} P_i + P_w + P_v - P_D + P_L\Big) + \mu_{11}(P_i - P_{i\min}) + \mu_{12}(P_{i\max} - P_i) \\ & + \mu_{21}(P_{i(t)} - P_{i(t-1)} - R_{idown}) + \mu_{22}(R_{iup} - P_{i(t)} + P_{i(t-1)}) \end{aligned} \tag{4}$$

s.t. $\beta_i + 2\gamma_i P_{i(t)} + w_i \xi_i \exp(w_i P_{i(t)}) + \lambda + \mu_{11} - \mu_{12} = 0$

$$\sum_{i=1}^{Ng} P_i + P_w + P_v = P_D + P_L$$

$$0 \le \mu_{11} \perp P_i - P_{i\min} \ge 0$$

$$0 \le \mu_{12} \perp P_{i\max} - P_i \ge 0$$

$$0 \le \mu_{21} \perp P_{i(t)} - P_{i(t-1)} - R_{idown} \ge 0$$

$$0 \le \mu_{22} \perp R_{iup} - P_{i(t)} + P_{i(t-1)} \ge 0$$

where $0 \le a \perp b \ge 0$ means $a \ge 0, b \ge 0, ab \ge 0$.

Define $\Phi(a,b) = a + b - \sqrt{(a^2 + b^2)}$,

$0 \le a \perp b \ge 0$ equals to $\Phi(a,b)$.

The single-objective model satisfied to KKT conditions is:

(5) $$Min \sum_{t=1}^{T} \sum_{i=1}^{Ng} a_i P_i^2(t) + b_i P_i(t) + c_i$$

s.t. $\beta_i + 2\gamma_i P_{i(t)} + w_i \xi_i \exp(w_i P_{i(t)}) + \lambda + \mu_{11} - \mu_{12} = 0$

$$\sum_{i=1}^{Ng} P_i + P_w + P_v = P_D + P_L$$

$$\Phi(\mu_{11}, P_i - P_{i\min}) = 0$$

$$\Phi(\mu_{12}, P_{i\max} - P_i) = 0$$

$$\Phi(\mu_{21}, P_{i(t)} - P_{i(t-1)} - R_{idown}) = 0$$

$$\Phi(\mu_{22}, Riup - P_{i(t)} + P_{i(t-1)}) = 0$$

The quantum genetic algorithm steps are as follows:

Step1. Initialization. Set initialized population $P(t) = \{p_1^t, p_2^t, \cdots, p_n^t\}$, *n* is population scale, $\mathrm{p}_j^t (j = 1, 2, \cdots, n)$ is an initial population *t*th generation, $\mathrm{p}_j^t = [\alpha_1^t, \alpha_2^t, \cdots, \alpha_m^t, \beta_1^t, \beta_2^t, \cdots, \beta_m^t]$ *m* is number of qubits. Initialized $\alpha,\ \beta$ are both defined to $1/\sqrt{2}$.

Step2 Observing $P(t_0)$. For every qubit, generate random numbers rand in [0, 1] by computer. If $rand \le |\alpha|^2$, take 0, otherwise take 1. So state $R(t_0)$ is got.

Step3 Decoding and fitness evaluation, save the most optimal value.

Step4 Set iterations *t=t+1*.

Step5 Structure $R(t) = \{a_1^t, a_2^t, \cdots, a_n^t\}$ according to probability amplitude values in *P(t)*, where a_j^t is a binary string long *m*.

Step6 Evaluate *R(t)* individuals and select the best one.

Step7 Judge pausing condition. Satisfied, output optimized individual, end algorithm; otherwise, continue.

Step8 Update quantum gate. $\begin{bmatrix} \alpha_i^{t+1} \\ \beta_i^{t+1} \end{bmatrix} = U \times \begin{bmatrix} \alpha_i^t \\ \beta_i^t \end{bmatrix}$, Where $\left[\alpha_i^t, \beta_i^t\right]^T$, $\left[\alpha_i^{t+1}, \beta_i^{t+1}\right]^T$ are *t*th qubit of *t*th and *t+1*th generation. *U* is the quantum revolving door: $U = \begin{bmatrix} \cos\theta, -\sin\theta \\ \sin\theta, \cos\theta \end{bmatrix}$, Where θ is rotation angle, $\theta = k \times f(\alpha, \beta)$. $f(\alpha_1, \beta_1)$ is set to ± 1 to control rotation direction, whose value can be looked up from Table 1. K is used to control algorithm convergence speed.

Step9 Create new optimal interval. Calculate distance between best values with the upper and lower limits, $r_{1i} = \left|\underline{x_i} - x_{besti}\right|, r_{2i} = \left|\overline{x_i} - x_{besti}\right|$, $\overline{x_i}, \underline{x_i}, x_{besti}$ are the upper and lower limits and best value of *i*th variable.

Step10 Repeat Step4 to Step 8 until termination condition meets. End.

Simulation results and discussion

The associated parameters are as the data shown in Table 1.The output power for wind power, load for thermal generators, total load and spinning reserved on some day are drawn in Figure 1. Hourly total solar radiation on horizontal surface is shown in Figure2. The B-coefficients are shown as follows. Two cases are calculated in this paper including wind power and PV power or not. Results are shown in Table 2.

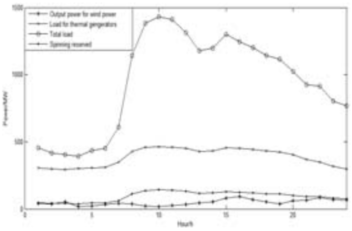

Fig.1. Relevant data of the simulation

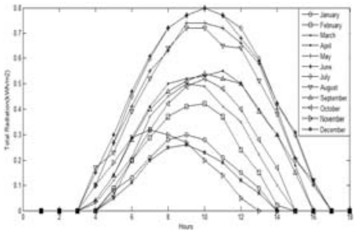

Fig.2 Hourly total radiation on horizontal surface

$$[B] = \begin{bmatrix} 0.0234, 0.0105, 0.0018, -0.0042, -0.0007, -0.0012 \\ 0.0105, 0.0167, 0.0020, -0.0064, -0.0005, -0.0023 \\ -0.0042, -0.0064, -0.0637, 0.3326, -0.0105, 0.0532 \\ -0.0007, -0.0005, -0.0060, -0.0105, 0.0118, 0.0006 \\ 0.0012, -0.0023, -0.0350, 0.0532, 0.0006, 0.2137 \end{bmatrix}$$

$$[B_0] = [-0.0006, 0.0015, -0.0039, 0.0062, 0.0015, 0.0013]$$

$$B_{00} = 0.0012$$

Table 1. The associated parameters of six thermal units

i	$PS_{i\max}$	$PS_{i\min}$	a_i	b_i	c_i	R_{iup}	R_{idown}	α_i	β_i	γ_i	ξ_i	ω_i
1	150	40	0.00144	5.88	80.62	35	45	4.071	-5.104	5.561	2.1×10-3	3.881
2	130	35	0.00532	4.61	100.12	30	40	3.321	-5.544	6.046	5.2×10-3	4.621
3	120	35	0.00415	6.09	234.08	30	40	3.746	-4.615	5.719	6.7×10-3	4.951
4	110	35	0.00384	6.22	220.78	30	40	3.981	-6.381	4.618	4.0×10-3	5.764
5	110	35	0.00277	7.04	240.19	30	40	4.351	-5.516	6.348	4.5×10-3	6.138
6	120	35	0.00508	7.88	320.47	35	45	4.120	-6.181	5.617	6.4×10-3	3.198

Table 2. The different total cost and computation time of CPU on some day when using the 3 different algorithms

Different algorithms	Without wind/PV power		With wind/PV power	
	Total cost	CPU time	Total cost	CPU time
GA	$280428	5.25	$219982	5.48
QGA	$279092	3.85	$217703	3.92
KKT-QGA	$277741	3.01	$214305	3.08

In this scenario, wind power, PV power and thermal power are simultaneously considered. The multi-objective model is as follows (*s.t.* Constraint conditions).

(6) $$min(\sum_{t=1}^{T}\sum_{i=1}^{Ng} a_i P_i^2(t)+b_i P_i(t)+c_i, \sum_{t=1}^{T}\sum_{i=1}^{Ng} \alpha_i+\beta_i P_i(t)+\gamma_i P_i^2(t)+\xi_i \exp(\omega_i P_i(t)))$$

Transform it into single-objective model, see section 3. Then we can get the single-objective model as follows.

(7) $$Min\sum_{t=1}^{T}\sum_{i=1}^{Ng} a_i P_i^2(t)+b_i P_i(t)+c_i$$

In order to validate the proposed KKT-Quantum Genetic Algorithm (KKT-QGA), two other different optimization algorithms including Genetic Algorithm (GA), Quantum Genetic Algorithm (QGA) are calculated and compared. Table 2 shows the total cost and CPU running time under the above operating conditions using the three different methods. From the table, we can obtain a clear result through the comparison of average convergence of power generation cost. With wind power, the total cost of KKT-QGA is $214305 which saves more cost than QGA and GA for $3398 and $5677, respectively. At the same time, the CPU running time convergence value of KKT-QGA method save more time than the QGA and GA methods at 0.84(s) and 2.40(s), respectively. So the results validate that the KKT-QGA method could obtain a faster speed which convergences to a minimum value of the total cost.

Only thermal power is considered. The multi-objective model is as follows.

(8) $$min(\sum_{t=1}^{T}\sum_{i=1}^{Ng} a_i P_i^2(t)+b_i P_i(t)+c_i, \sum_{t=1}^{T}\sum_{i=1}^{Ng} \alpha_i+\beta_i P_i(t)+\gamma_i P_i^2(t)+\xi_i \exp(\omega_i P_i(t)))$$

Transform it into single-objective model, see section 3. Then we can get the single-objective model as follows.

(9) $$Min\sum_{t=1}^{T}\sum_{i=1}^{Ng} a_i P_i^2(t)+b_i P_i(t)+c_i$$

As scenario 1, solve it by the proposed KKT-QGA, GA, and QGA. Table 2 shows the total cost and CPU running time under the above operating conditions using the three different methods. Compare results by KKT-QGA, the total cost of scenario with wind power and PV power is $214305 which significantly saves cost than without wind power and PV power, since wind power and PV power can save energy and reduce emissions. So higher wind power and PV power penetration levels can be selected to reduce power operation cost and energy consumption and emission cost.

Conclusions

A novel multi-objective optimization model is proposed in this paper to solve energy saving and emission reduction/economic dispatch in power system integrated wind/PV power using Karush-Kuhn-Tucker (KKT) algorithm and Quantum Genetic Algorithm(QGA). In addition to detailed model economic function, the paper also calculates energy saving and emission reduction benefit caused by wind and PV power and gives energy saving and emission reduction/economic dispatch model and their associated constraints. Then multi-objective optimization model is given. This multi-objective optimization is solved by the Karush-Kuhn-Tucker (KKT) algorithm and Quantum Genetic Algorithm (QGA). In the proposed algorithm, multi-objective problem is changed into a single-objective one by KKT frame and optimized by Quantum Genetic Algorithm. Two scenarios respectively consider scenes with wind/PV power and without solved by three different algorithms are given. Results show that proposed KKT-QGA method is more accurately and quickly than other algorithms.

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