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Research on Energy Transmission Capacity Improvement of the Aircraft Electric Power System

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A minimum transmission power loss calculation method is proposed, and the specific load configuration is obtained to improve energy transmission capability of the aircraft electric power system. The method is divided into three steps. First, a node table-style format of the aircraft electric power system is proposed according to its characteristics. Second, the transmission power loss equation is modeled by introducing the power flow calculation method. Third, the system transmission power losses with different load types are studied. Using particle swarm optimization algorithm, the minimum transmission power losses with different system load types are obtained. With the optimum load configuration, the transmission power loss is reduced and energy transmission capacity of the aircraft electric power system will be improved effectively.

Nomenclature

c_1, c_2	=	positive learning factors
$\bar{I}$	=	line thermal stability limit vector
$\dot{I}_{D1}$	=	current of load 1
$\dot{I}_{G1}$	=	current of generator 1
$\dot{I}_1$	=	current of bus 1
P_{D1}	=	active power of load 1
P_{D2}	=	active power of load 2
P_{G1}	=	active power of generator 1
P_{G2}	=	active power of generator 2
$P_{g,k}$	=	active power of the kth generator
P_i, Q_i	=	active and reactive power
P_L, Q_L	=	active- and reactive-power vectors of the load
$P_{L,d}$	=	active power of the dth generator
P_m, Q_m	=	active- and reactive-power vectors of the generator
$P_L^{\min}$, $P_L^{\max}$	=	upper- and lower-limit active-power vector of the load
$P_m^{\min}$, $P_m^{\max}$	=	upper- and lower-limit active-power vectors of the mth generator
Q_{D1}	=	reactive power of load 1
Q_{D2}	=	reactive power of load 2
Q_{G1}	=	reactive power of generator 1
Q_{G2}	=	reactive power of generator 2
$Q_m^{\min}$ and $Q_m^{\max}$	=	upper- and lower-limit reactive-power vectors of the mth generator
r_1, r_2	=	uniform random number between 0 and 1
S_{D1}	=	apparent power of load 1
S_{D2}	=	apparent power of load 2
S_{G1}	=	apparent power of generator 1
S_{G2}	=	apparent power of generator 2
S_1	=	apparent power of bus 1
S_2	=	apparent power of bus 2
$\dot{U}_1$	=	voltage of generator 1
$\dot{U}_2$	=	voltage of generator 2
$V^{\min}$, $V^{\max}$	=	upper- and lower-limit vectors of the node voltage
Y_{11}, Y_{12}	=	admittance matrixes
y_p	=	parallel admittance
y_s	=	series admittance
w	=	inertia weight factor

I. Introduction

AN AIRCRAFT electric power system is the system of electric energy generation, modulation, control, transformation, transmission, and distribution. As the improvement of performance requirements of modern aircraft, more electronic equipments are used. The dependence on the aircraft electric power system is also growing. With the more-electric aircraft and all-electric aircraft development, higher requirements of power quality and transmission capacity will be needed [1]. However, due to the characteristics of the aircraft electric power system, its power frequency is high. Therefore, the load type has a greater impact on the transmission capacity of aircraft electric power system. How to design appropriate loads in the specific situations to reduce power losses during transmission is an urgent problem.

However, the present research of the aircraft electric power system is mainly focused on simulation, fault diagnosis, prognostics, and health management [2–5]. There is still little research on the electric energy transmission capacity.

Power flow is the most frequently performed study for power systems. Power flow calculation is an essential and fundamental tool in power system operation, planning, and energy management [6]. As the basis of analyzing and controlling power systems, power flow calculations have been extensively researched and widely used [7–13]. Power flow calculation is needed for both steady-state power flow analysis and initializations for different dynamic analyses, and these problems must be solved by some efficient methods [14]. Hence, many methods to solve the power flow have been developed and well documented in the last few decades [15]. Gauss–Seidel, Newton–Raphson, and fast decoupled load flow are the three powerful traditional power flow calculation methods and can solve most power flow problems in electric power systems. Though power flow calculation methods are widely used in power systems, they have not been used to analyze aircraft electric power systems.

In view of the above, this paper proposes a node representation of a typical four-generator aircraft electric power system in accordance with the general similarity of a power system and its characteristics. Then the power flow calculation method is introduced to obtain the transmission loss equations of aircraft electric power system. The impact on transmission power loss with different loads is also analyzed. Particle swarm optimization algorithm is also used to obtain the load type with minimum loss of power transmission.

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Finally, comparing the minimum power losses under different conditions, the optimal load configuration will be obtained.

The remainder of this paper is organized in the following way. In Sec. II, a node representation of a typical four-generation aircraft electric power system is proposed. In Sec. III, we present the power flow calculation method. And the optimization model and optimization algorithm are also explained. Section IV presents the simulation analysis with different types and the optimum load is obtained. Finally, we draw the conclusion of the paper.

II. Power Transmission Loss Modeling

A. Form Transformation of Aircraft Electric Power System

An aircraft electric power system is an independent power system. Compared with a general electric power system, it has its own characteristics, such as a concentrated power supply, more switches, and so on. Therefore, the representative form of an aircraft electric power system must be transformed to meet the needs of power transmission loss modeling.

Figure 1 shows a typical four-generator aircraft electric power system. Under normal conditions, generator 1 and generator 2 (called group 1) are in parallel operation, and generator 3 and generator 4 (called group 2) are in parallel operation. Group 1 and group 2 are not parallel running. Switching impacts to energy transmission are substituted with the different parameters of the transmission line. The transformed representation of aircraft electric power system is shown in Fig. 2.

B. Establishment of Transmission Power Loss

Comparing Fig. 2 with a standard IEEE nine-bus system [16], the conclusion can be obtained that power flow calculation can also be used to calculate the transmission power loss of aircraft electric power system.

The calculation process is as follows, taking two generators system, for example, as shown in Fig. 3. The transmission line model is as shown in Fig. 4.

According to power flow method [17], Eqs. (1–4) can be obtained as

$$S_1 = (P_{G1} - P_{D1}) + j(Q_{G1} - Q_{D1}) \tag{1}$$

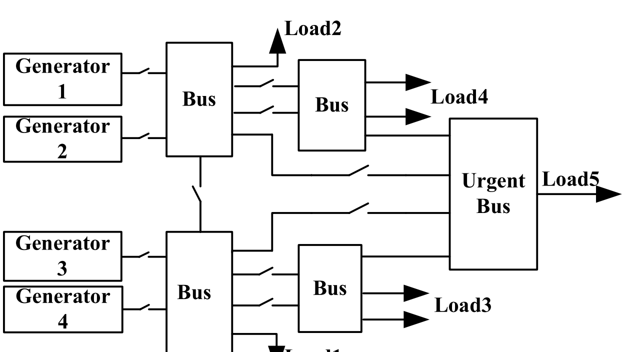


Fig. 1 Typical aircraft electric power system.

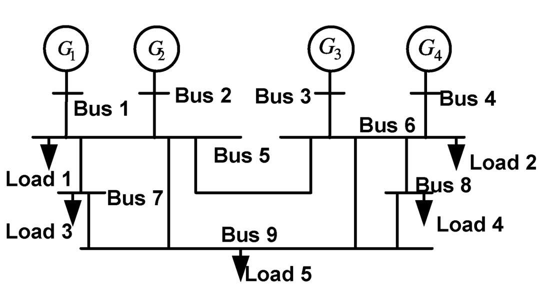


Fig. 2 Representation form of the aircraft electric power system.

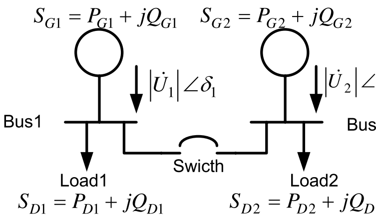


Fig. 3 Two-generator power system.

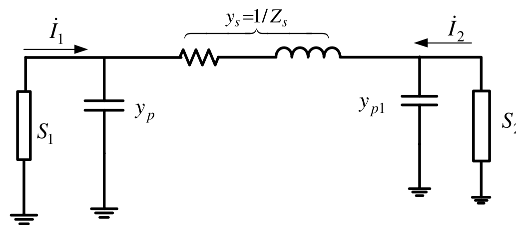


Fig. 4 Model of transmission line.

$$S_2 = (P_{G2} - P_{D2}) + j(Q_{G2} - Q_{D2}) \tag{2}$$

$$\dot{I}_1 = (y_p + y_s)\dot{U}_1 + (-y_s)\dot{U}_2 = Y_{11}\dot{U}_1 + Y_{12}\dot{U}_2 \tag{3}$$

$$\dot{I}_2 = (-y_s)\dot{U}_1 + (y_p + y_s)\dot{U}_2 = Y_{21}\dot{U}_1 + Y_{22}\dot{U}_2 \tag{4}$$

For the system with n buses, as shown in Fig. 5, the equation of the ith bus is

$$\dot{I}_i = Y_{i1}\dot{U}_1 + Y_{i2}\dot{U}_2 + \cdots + Y_{in}\dot{U}_n = \sum_{k=1}^{n} Y_{ik}\dot{U}_k \tag{5}$$

Then

$$P_i - jQ_i = \dot{U}_i^* I_i = \dot{U}_i^* \sum_{k=1}^{n} Y_{ik}\dot{U}_k \tag{6}$$

where

$$P_i = \mathrm{Re}[\dot{U}_i^* \sum_{k=1}^{n} Y_{ik}\dot{U}_k] \qquad Q_i = -\mathrm{Im}[\dot{U}_i^* \sum_{k=1}^{n} Y_{ik}\dot{U}_k]$$
$$k = 1, 2, \ldots, n$$

Suppose that S_{ik} and S_{ki} are the line powers of bus i and bus k. The power equations can be obtained as

$$S_{ik} = P_{ik} + jQ_{ik} = \dot{U}_i(\dot{U}_i^* - \dot{U}_k^*)y_{ik}^* + |U_i|^2 y_{pi} \tag{7}$$

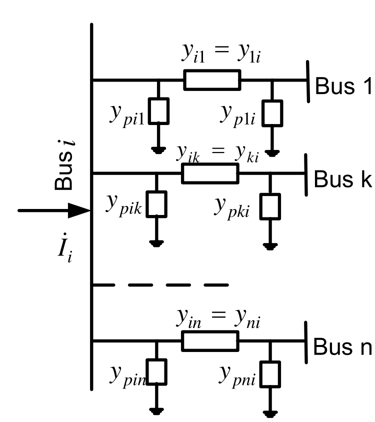


Fig. 5 System of n buses.

$$S_{ki} = P_{ki} + jQ_{ki} = \dot{U}_k(\dot{U}_k^* - \dot{U}_i^*)y_{ki}^* + |U_k|^2 y_{pk} \tag{8}$$

Then the transmission loss of bus i to k is

$$S_{\text{Loss-}ik} = S_{ik} + S_{ki} \tag{9}$$

III. Optimization Designing

A. Optimization Model

According to the characteristics of the system, looking for the minimum power loss, the objective function is

$$\min \sum_{k=1}^{n} \sum_{i=1}^{n} S_{\text{Loss-}ik} \tag{10}$$

The constraint equations are

$$P_m - P_L - P(V, \theta) = 0 \tag{11}$$

$$Q_m - Q_L - Q(V, \theta) = 0 \tag{12}$$

The power constraint is

$$\sum_{k\in\Omega} P_{g,k} = \sum_{d\in\Omega} P_{L,d} + \sum_{k=1}^{n} \sum_{i=1}^{n} S_{\text{Loss-}ik} \tag{13}$$

The line heat-stable bound is

$$|I(V, \theta)| \le \bar{I} \tag{14}$$

The node voltage magnitude constraint is

$$V^{\min} \le V \le V^{\max} \tag{15}$$

The generator active- and reactive-power constraints are

$$P_m^{\min} \le P_m \le P_m^{\max} \tag{16}$$

$$Q_m^{\min} \le Q_m \le Q_m^{\max} \tag{17}$$

The load constraint is

$$P_L^{\min} \le P_L \le P_L^{\max} \tag{18}$$

B. Particle Swarm Optimization

For the aircraft electric power system, as shown in Fig. 1, an appropriate optimization algorithm must be used to obtain the optimal load to minimize the system transmission power loss. Particle swarm optimization (PSO) is an optimization algorithm that is widely used for solving global optimization problems. It was originally proposed by Kennedy and Eberhart [18].

A PSO algorithm is easy to implement with low CPU speed requirements. However, the PSO algorithm itself is a group of intelligent optimization algorithms, which also exist in the problem of trapping into the local optimum. Especially when the system is relatively complex, with more local extreme values, the easier it will be trapped into local optimum. Therefore, many researchers are devoted to solving this problem. Angeline [19] incorporated PSO with an explicit selection mechanism to improve PSO. Shi et al. [20] presented a hybrid evolutionary algorithm based on PSO and genetic algorithm (GA) methods through crossing over PSO and GA, which possess better ability to find the global optimum than that of the standard PSO algorithm. Wang and Li [21] integrated PSO and simulated annealing to improve the performance of PSO. Jiang et al. [22] proposed an improved particle swarm optimization.

In this paper, a population of points is sampled randomly from the feasible space. Then the population is partitioned into several subswarms, each of which is made to evolve based on PSO. The traditional PSO algorithm initializes a group of random particles at first. Then particles are just following the current optimum particles to search the optimal solution in the solution space. Suppose that position and velocity of the mth particle in d-dimensional space are $X^m = (x_{m,1}, x_{m,2}, \ldots, x_{m,d})$ and $V^m = (v_{m,1}, v_{m,2}, \ldots, v_{m,d})$. The particles update their own value by tracking the two best values. The first one is the optimal solution of the particle $Q^m = (q_{m,1}, q_{m,2}, \ldots, q_{m,d})$, and the second is the global optimal solution Q^g.

Finding these two optimal values, the particles update their own velocity and a new location as follows:

$$v_{m,j}(t+1) = wv_{m,j}(t) + c_1 r_1[q_{m,j} - x_{m,j}(t)] + c_2 r_2[q_{g,j} - x_{m,j}(t)] \tag{19}$$

$$x_{m,j}(t+1) = x_{m,j}(t) + v_{i,j}(t+1), \qquad j = 1, 2, \cdots, d \tag{20}$$

The velocity range is $[-v_{\max}, v_{\max}]$.

In this paper, the improved particle swarm algorithm is presented. In the calculation process, the space will be randomly divided into a number of subgroups. Each subgroup updates the particle position and velocity. After several generations, in order to achieve information sharing, subgroups are mixed and then reallocated.

IV. Simulation and Analysis

According to the characteristics of the aircraft electric power system, the system has four generators, nine nodes, and five loads. The active-power range of each generator is $[P^{\min}, P^{\max}] = [10\text{ kW}, 80\text{ kW}]$, and the reactive-power range of each one is $[Q^{\min}, Q^{\max}] = [0\text{ kvar}, 80\text{ kvar}]$. The parameters of transmission lines between nine nodes are shown in Table 1. Total apparent power load is 180.28 kVA and remained unchanged in various conditions.

The initial conditions are that the load is divided into two categories. Load 5 belongs to type II, and its active and reactive powers are $[P_{L-\mathrm{II}}, Q_{L-\mathrm{II}}] = [50\text{ kW}, 20\text{ kvar}]$. Others belong to type I, and the active and reactive powers are $[P_{L-\mathrm{I}}, Q_{L-\mathrm{I}}] = [30\text{ kW}, 10\text{ kvar}]$. It means that the loads are in a symmetrical distribution. From Eq. (9), the original transmission power loss of the system is $P_{\text{losses}} = 1.847$ W.

To illustrate the problem, the simulations are divided into five conditions. First, analyze the impacts to power losses when only active and reactive powers of type I are changed, while keeping the type II unchanged. Second, while keeping type I and changing the active and reactive powers of type II, analyze the impacts. Third, while maintaining the location and apparent power of existing loads, analyze the impacts to the power losses when both load types are changed. Fourth, keeping the existing loads' apparent powers unchanged and changing their locations, research the impacts of locations to the transmission power losses. Finally, keeping the system total apparent power and changing the loads into the same, study the impact to the transmission power losses when active and reactive powers are changed.

Under every condition, the minimum power loss is obtained with PSO. In the PSO process, each active or reactive power is viewed as a particle. The space will be divided into a number of subgroups with

Table 1 Line parameters

Line	Impedance/p.u.	Reactance/p.u.
1–5	0	0.0576
2–5	0.0170	0.0920
3–6	0.0390	0.1700
4–6	0	0.0586
5–7	0.0119	0.1008
5–8	0.0085	0.0720
6–8	0	0.0625
7–9	0.0320	0.1610
8–9	0.0100	0.0850

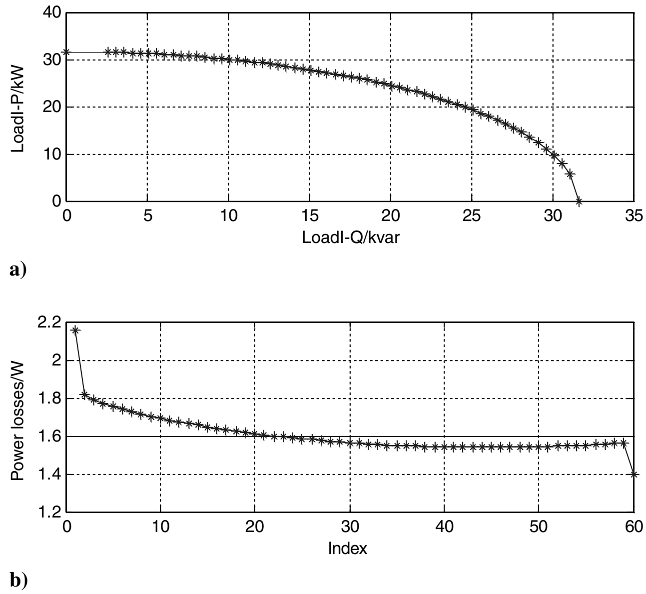


Fig. 6 Active and reactive powers of load type I and the transmission power losses.

unchanged as in the original system, the load active and reactive powers are changed between the two extreme points of only the active and only the reactive powers. The simulation result with this condition is shown as in Fig. 7. When changing the active and reactive powers of type II, system transmission power losses of aircraft electric power system will be also changed, and there is also a minimum power loss in this condition. Using PSO, the minimum power loss is obtained as 1.5384 W, which is 83.30% of the original system. The load configuration of type II is that active power is 1.850 kW, and reactive power is 53.8182 kvar.

3) Analyze the impacts to the power loss when active and reactive powers of both load types are changed. Maintaining the load itself with apparent power unchanged as in the original system, the load active and reactive powers are changed between the two extreme points of only the active and only the reactive powers. The simulation results are shown in Fig. 8, where Fig. 8a indicates the type 1 load variation curves of active power and reactive power and Fig. 8b is the system transmission power losses. Figure 8 shows that with the load changes, the system transmission power loss looks like a bathtub curve. It means only active-power or only reactive-power load is not effective at reducing transmission power loss. When the system load has an appropriate ratio of active power and reactive power, the system transmission power loss is minimized and the system is optimal. Therefore, it is necessary to adopt appropriate optimization algorithm to obtain the optimal active- and reactive-power ratios of the load to achieve the purpose of improving the system transmission capacity. Using PSO, the optimal active and reactive powers of the loads with minimum line transmission power loss are as shown in Table 2. Compared with existing systems, the transmission power losses with the optimal load are 86.25% of the original system, which increase the system's transmission capacity significantly.

4) With a fixed load value, research the impacts of the load position to the transmission power losses. This step studies the transmission power losses with different load locations. Consider the situation in which the load values are the same with the initial configuration, and type II is varied between load 1 and load 5. There is only one load with type II, and the others are type I. The simulation results are shown in Table 3. From Table 3, the relationship between power loss and load location is obvious for the entire system. Relative to the existing system, after changing the locations, the transmission power losses are 80.08, 76.56, 98.97, and 82.13% of the original system. For a fixed-load system, according to the system characteristics, the most appropriate access methods to effectively improve the system transmission capacity can be found . For this system, the optimal load configuration at this time is load 2 with type II and the rest with type I.

active or reactive powers. Under certain conditions, minimum power loss will be obtained.

After simulation, comparing the minimum power loss of the five conditions, the final optimal load configuration will be obtained.

The simulation and analysis process is as follows:

1) Analyze the impacts to power losses when only active and reactive powers of type I are changed. Maintaining the apparent power of type I unchanged as in the original system, the load active and reactive powers are changed between the two extreme points of only the active and only the reactive powers. The simulation result is shown as in Fig. 6. It can be see from the figure that changing active and reactive powers of type I will impact the system transmission power losses of aircraft electric power system, and there is a minimum power loss in this condition. Using PSO, the minimum power loss is obtained as 1.400 W, which is 75.80% of the original system. The load configuration of type I is that active power and reactive power are 0 kW and 31.62 kvar.

2) Keeping type I while changing the active and reactive powers of type II, analyze the impacts. Keeping the apparent power of type II

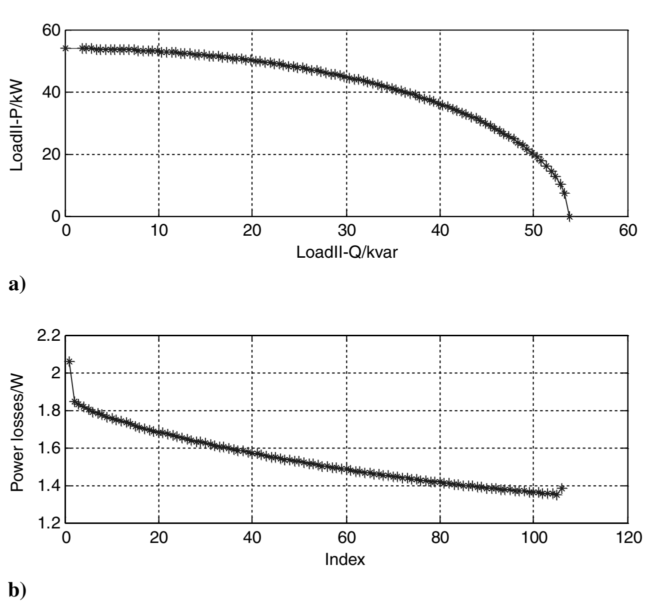


Fig. 7 Active and reactive powers of load type II and the transmission power losses.

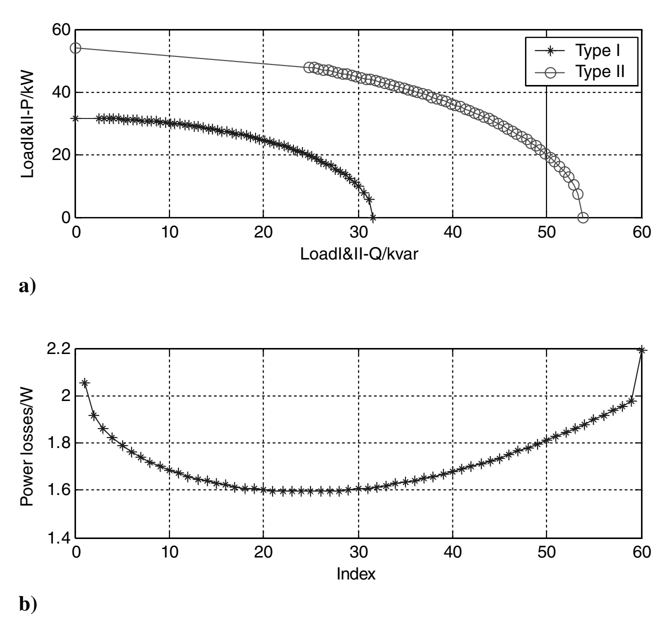


Fig. 8 Load active- and reactive-power curves and the power losses.

Table 2 Comparison before and after optimization

Power	$P_{L-\mathrm{I}}$/kW	$Q_{L-\mathrm{I}}$/kvar	$P_{L-\mathrm{II}}$/kW	$Q_{L-\mathrm{II}}$/kvar	Losses/W
Original	30.000	10.000	50.000	20.000	1.847
New	19.620	24.797	41.850	33.888	1.593

Table 3 Load number of type II and transmission power loss

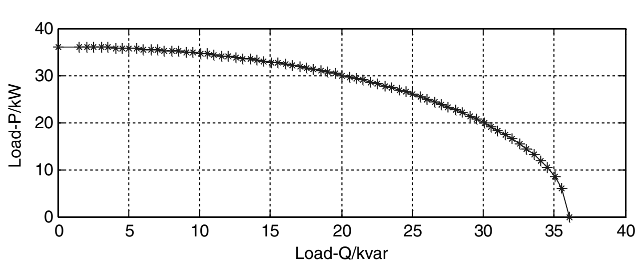
Load number of type II	Power losses/W
Load 1	1.479
Load 2	1.414
Load 3	1.828
Load 4	1.517

5) When all the loads are the same, analyze the impact to the transmission power losses with different active- and reactive-power ratios of the load.

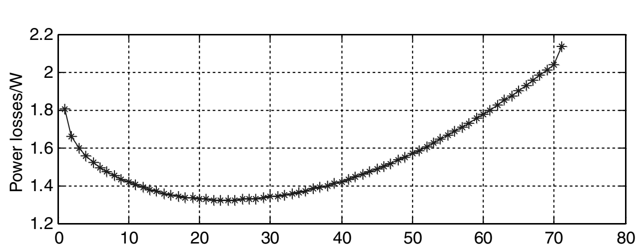
When loads are all the same and the total apparent power is maintained at 180.28 kW, the relationship between transmission power loss and load power is as shown in Fig. 9. Figure 9a shows the load active- and reactive-power curves. The vertical axis is the active-power value, and the abscissa is the value of reactive power. Figure 9b is the system transmission power loss curves with the load changing. It can be seen from Fig. 9b, with the proportion of load active and reactive powers changing, that transmission power is also changing like a bathtub curve. Therefore, a specific proportion of active and reactive powers in this condition must exist with the minimum transmission power loss.

With the PSO algorithm, the minimum transmission power loss is 1.3228 W in this condition. The load configuration active power is 24.056 kW and reactive power is 26.258 kvar. Compared with the original system, the power loss is 71.62% of the original system.

With the above five kinds of conditions, we compare the transmission power losses. It can be seen that in this system, the power losses existed in the system with the same load type. Therefore, it can be concluded that when all loads are the same, where active power is 24.056 kW and reactive power is 26.258 kvar, the power loss is minimum, which equals 1.3228 W. And at this time, the transmission power loss is 71.62% of the original system. This load configuration improves the system of energy transmission capacity effectively.



a)



b)

Fig. 9 Load active and reactive powers and the power losses.

V. Conclusions

A node table-style format of the aircraft electric power system is proposed. The transmission power loss equations are modeled by introduction of the power flow calculation method. Using particle swarm optimization algorithm, the minimum transmission power loss is obtained with the different system load types. Comparing the different load types impacting the power losses, the optimal load configuration is obtained.

References

[1] Chang, J., and Wang, A. H., "New VF-Power System Architecture and Evaluation for Future Aircraft," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 42, No. 2, April 2006, pp. 527–539. doi:10.1109/TAES.2006.1642569

[2] Eid, A., El-Kishky, H., Abdel-Salam, M., and El-Mohandes, M. T., "On Power Quality of Variable-Speed Constant-Frequency Aircraft Electric Power Systems," *IEEE Transactions on Power Delivery*, Vol. 25, No. 1, Jan. 2010, pp. 55–65. doi:10.1109/TPWRD.2009.2031672

[3] Ma, C., Gu, X., and Wang, Y., "Fault Diagnosis for Power Electronic System with Fault Gradation using Assembly Neural Network Group," *Third International Conference on Natural Computation*, Aug. 2007, pp. 277–281.

[4] Keller, K., Swearingen, K., Sheahan, J., Bailey, M., Dunsdon, J., Przytula, K. W., Jordan, B., "Aircraft Electrical Power Systems Prognostics and Health Management," *IEEE Aerospace Conference*, Inst. of Electrical and Electronics Engineers, Piscataway, NJ, 2006, pp. 1–12.

[5] Eid, A., Abdel-Salam, M., El-Kishky, H., and El-Mohandes, T., "Simulation and Transient Analysis of Conventional and Advanced Aircraft Electric Power Systems with Harmonics Mitigation," *Electric Power Systems Research*, Vol. 79, No. 1, Jan. 2009, pp. 80–88. doi:10.1016/j.epsr.2008.05.005

[6] Radman, G., and Raje, R. S., "Power Flow Model/Calculation for Power Systems with Multiple Facts Controllers," *Electric Power Systems Research*, Vol. 77, No. 12, Oct. 2007, pp. 1521–1531. doi:10.1016/j.epsr.2006.10.008

[7] Zhang, X.-P., "Fast Three Phase Load Flow Methods," *IEEE Transactions on Power Systems*, Vol. 11, No. 3, Aug. 1996, pp. 1547–1554. doi:10.1109/59.535696

[8] Abdel-Akher, M., Nor, K. M., and Rashid, A. H. A., "Improved Three-Phase Power-Flow Methods Using Sequence Components," *IEEE Transactions on Power Systems*, Vol. 20, No. 3, Aug. 2005, pp. 1389–1397. doi:10.1109/TPWRS.2005.851933

[9] Grijalva, S., Sauer, P. W., and Weber, J. D., "Enhancement of Linear ATC Calculations by the Incorporation of Reactive Power Flows," *IEEE Transactions on Power Systems*, Vol. 18, No. 2, May 2003, pp. 619–623. doi:10.1109/TPWRS.2003.810902

[10] Peças Lopes, J. A., Moreira, C. L., and Madureira, A. G., "Defining Control Strategies for Micro Grids Islanded Operation," *IEEE Transactions on Power Systems*, Vol. 21, No. 2, May 2006, pp. 916–924. doi:10.1109/TPWRS.2006.873018

[11] Wu, W. C., and Zhang, B. M., "A Three-Phase Power Flow Algorithm for Distribution System Power Flow Based on Loop-Analysis Method," *International Journal of Electrical Power and Energy Systems*, Vol. 30, No. 1, Jan. 2008, pp. 8–15. doi:10.1016/j.ijepes.2007.06.005

[12] Jang, G. S., Hur, D., Park, J.-K., and Lee, S. H., "A Modified Power Flow Analysis to Remove a Slack Bus with a Sense of Economic Load Dispatch," *Electric Power Systems Research*, Vol. 73, No. 2, Feb. 2005, pp. 137–142. doi:10.1016/j.epsr.2004.07.001

[13] Echavarren, F. M., Lobato, E., and Rouco, L., "A Power Flow Solvability Identification and Calculation Algorithm," *Electric Power Systems Research*, Vol. 76, No. 4, Jan. 2006, pp. 242–250. doi:10.1016/j.epsr.2005.06.006

[14] Acharjee, P., and Goswami, S. K., "A Decoupled Power Flow Algorithm Using Particle Swarm Optimization Technique," *Energy Conversion and Management*, Vol. 50, No. 9, 2009, pp. 2351–2360. doi:10.1016/j.enconman.2009.05.018

[15] Kulworawanichpong, T., "Simplified Newton-Raphson Power-Flow Solution Method," *International Journal of Electrical Power and Energy Systems*, Vol. 32, No. 6, July 2010, pp. 551–558.

doi:10.1016/j.ijepes.2009.11.011

[16] Ai, D., Bao, H., and Yang, Y., "A New Method of Calculating Generation Linear Distribution Factors by Least Square Fitting," *International Conference on Sustainable Power Generation and Supply*, April 2009, pp. 1–5.

[17] Al-Rashidi, M. R., and El-Hawary, M. E., "Applications of Computational Intelligence Techniques for Solving the Revived Optimal Power Flow Problem," *Electric Power Systems Research*, Vol. 79, No. 4, April 2009, pp. 694–702. doi:10.1016/j.epsr.2008.10.004

[18] Kennedy, J., and Eberhart, R., "Particle Swarm Optimization," *Proceedings of the IEEE International Conference on Neural Networks*, Inst. of Electrical and Electronics Engineers, Piscataway, NJ, Nov.–Dec. 1995, pp. 1942–1948.

[19] Angeline, P. J., "Using selection to improve particle swarm optimization," *Proceedings of the IEEE Congress on Evolutionary Computation*, Inst. of Electrical and Electronics Engineers, Piscataway, NJ, May 1998, pp. 84–89.

[20] Shi, X. H., Lu, Y. H., Zhou, C. G., Lee, H. P., Lin, W. Z., and Liang, Y. C., "Hybrid evolutionary algorithms based on PSO and GA," *Proceedings of the IEEE Congress on Evolutionary Computation 2003*, Inst. of Electrical and Electronics Engineers, Piscataway, NJ, Dec. 2003, pp. 2393–2399.

[21] Wang, X.-H., and Li, J.-J.., "Hybrid Particle Swarm Optimization with Simulated Annealing," *International Conference on Machine Learning and Cybernetics*, Shanghai, 26–29 Aug. 2004, pp. 2402–2405.

[22] Jiang, Y., Hu, T., Huang, C.-C., and Xianing, W., "An Improved Particle Swarm Optimization Algorithm," *Applied Mathematics and Computation*, Vol. 193, No. 1, Oct. 2007, pp. 231–239. doi:10.1016/j.amc.2007.03.047