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Intelligent Maintenance Scheduling System for Maximum Performance of Solar-Energy-Generating System

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In this research, an intelligent maintenance scheduling system for gaining the maximum performance of a solar-energy-generating system is proposed. In the system, the particle swarm optimization (PSO) algorithm is used for the intelligent maintenance scheduling of the solar-energy-generating system. The maintenance center receives many maintenance prescription requests from all solar-energy-generating stations. For various uncertainties, the optimal solution of maintenance scheduling is considered. To reduce maintenance costs and improve maintenance efficiency, the intelligent scheduling system using the PSO method is constructed. In the maintenance scheduling model, the maintenance time and prework time are set to be the optimal computing parameters, and the lowest cost is set to be the optimal target. By design and implementation, we can determine the advantages of the PSO-based intelligent system. It meets both requirements of real time and integration for intelligent systems. Experimental results show the advantages of the intelligent maintenance scheduling system for the maximum performance of the solar-energy-generating system; that is, such a scheduling system meets both requirements of efficiency and lowest cost for the intelligent maintenance of the solar-energy-generating system.

1. Introduction

In recent years, the development of solar-energy-generating systems has continued to flourish. In the reduction of maintenance costs and improvement of maintenance efficiency, the maintenance scheduling of solar-energy-generating systems is becoming increasingly important. In 2006, Hong and Li[1] proposed the short-term generation scheduling of an autonomous system, using genetic algorithms. Such scheduling deals with an independent generation system for wind power, solar power, a diesel unit, and a rechargeable battery group. It considers the uncertain factors of climate and investigates the short-term generation scheduling of the above-mentioned independent generation system. The cost of diesel units is minimized and all operation constraints are satisfied. The solar power and wind power modeled by the fuzzy theory are expressed with the Lagrange multiplier and membership function for reducing the computational complexity using the genetic

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algorithm with the penalty function. The results of simulations showed the applicability of the proposed method. In 2006, Lo[2] proposed that the outage scheduling for system expansion or/and maintenance is a regular work in distribution systems. In rule-based programming, composite load patterns were used to evaluate the reliability index "Energy Not Supplied (ENS)". Using ENS, the tables of the set of reliability grade variations (SRGV) were proposed. The SRGV tables were applied to observe the constraints more easily, and a suitable schedule was evaluated in advance. By verifying the effectiveness of the proposed approaches, the proposed methodologies provide effective performance. From the perspective of carriers, long- and middle-term aircraft maintenance scheduling models in accordance with the related constraints in actual operations were developed by Yuan[3] in 2006. Yuan considered both the objectives of the minimum aircraft maintenance cost of the carrier's own fleet and the maximum maintenance revenue of its customers' aircraft to develop a long-term model formulated as a multiple-objective zero-one integer program. In addition, since the middle-term model must be developed after the season's flight timetables have been determined, the middle-term model based on the season's flight timetable and long-term model's results was developed. Yuan applied mathematical programming techniques to construct long- and middle-term aircraft maintenance scheduling models. These two models are formulated as zero-one integer problems. Note that the long-term model of aircraft maintenance schedules has two objective functions. Thus, Yuan applied the weighting method to deal with the multiple-objective model. The particle swarm optimization (PSO) algorithm with a modified SR-2 decoding method was used to solve the heterogeneous fixed fleet vehicle routing problem (HFFVRP) by Hu[4] in 2013. Finally, the proposed metaheuristics were applied to eight benchmark test problems from Golden to demonstrate the applicability and practicability of PSO (SR-2). The computational results show that our PSO (SR-2) has generated one best-known solution and the average deviation of all the test problems is 2.46%. In 2015, Li[5] proposed a resource scheduling method for predictive maintenance services of equipment whose location changes dynamically, aiming at eliminating potential failure and minimizing service and outage costs, considering the technicians' ability to differentiate the maintenance task, fault prediction information, equipment operation plan, and other constraints. This study adopts a hybrid algorithm to resolve a mathematical model that is set to describe this problem. Lastly, the results indicating the best time of servicing, route planning, and suitable technician show that this method can improve the service level and reduce the total cost.

Service resource scheduling is the key step in product service delivery and depends on the knowledge obtained from past service data and product information in the process used, namely, the different fault maintenance scheme, technicians' skill, equipment state information, fault prediction information, and work plan. On the basis of this step, in 2016, Papa[6] proposed a proactive maintenance service platform architecture based on cyber physical systems. The platform allows the estimation of future performance, the prediction and prevention of imminent failures, and the scheduling of proactive maintenance. Maintenance is an important element that creates added value in business processes and also creates new business models with a stronger service orientation. Physical systems and the environment they work in are continuously monitored by a range of intelligent sensors, resulting in massive amounts of data characterizing the usage history, working conditions, location, movement, and other physical properties of the systems. These systems are part of a larger network of heterogeneous and collaborative systems (e.g., vehicle fleets) connected via robust communication mechanisms and are able to operate in challenging environments. The network consists of distributed processing chains that efficiently transform raw data into knowledge while minimizing the need for bandwidth. Sophisticated distributed sensing and decision-making functions are performed at different levels collaboratively, ranging from local nodes that locally optimize performance, bandwidth, and maintenance to cloud-based platforms that integrate information from diverse systems and execute distributed processing and analytics algorithms for global decision-making. In 2016, Rao(7) proposed an intelligent approach towards the fault diagnostics of a solar microgrid with a battery backup for a reliability-centered maintenance approach to supersede and improve the preventive maintenance strategy. Rao also proposed the analysis of a comprehensive list of faults that may occur in a photovoltaic (PV) microgrid, the parameters required to correctly diagnose and classify the faults and finally select a minimum number of sensors, and data acquisition required for the reliability centered maintenance of a PV-based microgrid. In 2017, Tzeng(8) proposed an energy storage monitoring system for wind and solar power generations, which is a centralized maintenance model. Because of Taiwan's solar energy and wind power generation system becoming smaller and more popular, the battery energy storage will be used to overcome smaller conversion rates and less stable power generation, and it will be connected to the power grid to stabilize the output. The current, voltage, charge and discharge times of each battery, the state of charge of the battery, and charging of abnormal warming should be monitored to achieve timely warning control, shorten the maintenance time, and improve the overall energy efficiency. This maintenance model is primarily focused on monitoring the device limitations.

Thus, it is very important to reduce maintenance costs and improve maintenance efficiency for solar-energy-generating systems. Therefore, it is necessary to build the intelligent scheduling system using the PSO method in order to reduce maintenance costs and improve maintenance efficiency.

2. Maintenance Scheduling System

2.1 Model of maintenance scheduling for solar-energy-generating system

Considering the minimum cost for the optimization of the PSO method and the parameters of maintenance scheduling shown in Table 1, we can build a model of maintenance scheduling for the solar-energy-generating system.

2.2 Architecture of maintenance scheduling for solar-energy-generating system

The architecture of maintenance scheduling for the solar-energy-generating system using the PSO method is shown in Fig. 1. Computing engines, such as the prediction engine (using the fuzzy method), diagnosis engine (using the fuzzy method), prescription engine (using the fuzzy method), scheduling engine (using the PSO method), and check engine (using the fuzzy method), are built on Azure. We can install temperature and irradiance sensors on the solar-energy-generating system, and transmit the sensing data by Zigbee, RJ45 (TCP), RS-232, and SUZAKU real-time processes. By a wireless access point, the signal is transmitted to the cloud database to integrate the dust subsystem and finally combine the cloud of the dust system, named the cloud-dust architecture. The cloud-dust architecture is used for the implementation of records, monitoring, prediction, assessment, diagnosis, prescriptions, scheduling, and foolproofing check.

Table 1
Parameters of maintenance scheduling for solar-energy-generating system.

Parameter	Parameter meaning
Photovoltaic build cost (*PVBC*)	Cost of the initial building of a photovoltaic system
Photovoltaic kilowatt (*PVK*)	Wattage of the initial building of a photovoltaic generation system
Photovoltaic cost (*PVC*)	Generation cost of photovoltaic system
Photovoltaic repurchased cost by Taipower (*PVRC*)	Photovoltaic generation cost repurchased by Taipower
Income cost (*IC*)	Actual income of photovoltaic system
Photovoltaic power (*Pdc*)	Photovoltaic panels' real-time output power
Photovoltaic power prediction (*Ppre*)	Photovoltaic panels' real-time power prediction expectation
Power error (*Pe*)	Difference between measured power value real-time output by photovoltaic panel from predicted one
Photovoltaic loss cost (*PVLC*)	Loss generation cost of photovoltaic system
Preparation time (*RT*)	Maintenance of photovoltaic system before latency
Maintenance time (*MT*)	Photovoltaic maintenance time
Power loss (*PL*)	Photovoltaic panel output power measurement and prediction real-time difference value
Photovoltaic repairs (PVR)	Photovoltaic system of repairs
Photovoltaic system numbers (*i*)	Total amount of photovoltaic system maintenance
Maintenance scheduling cost (*MSC*)	Minimum cost of photovoltaic system optimal maintenance scheduling
Total time (*TT*)	No. of working hours of maintenance scheduling
Maintenance team (Mteam)	Photovoltaic maintenance team

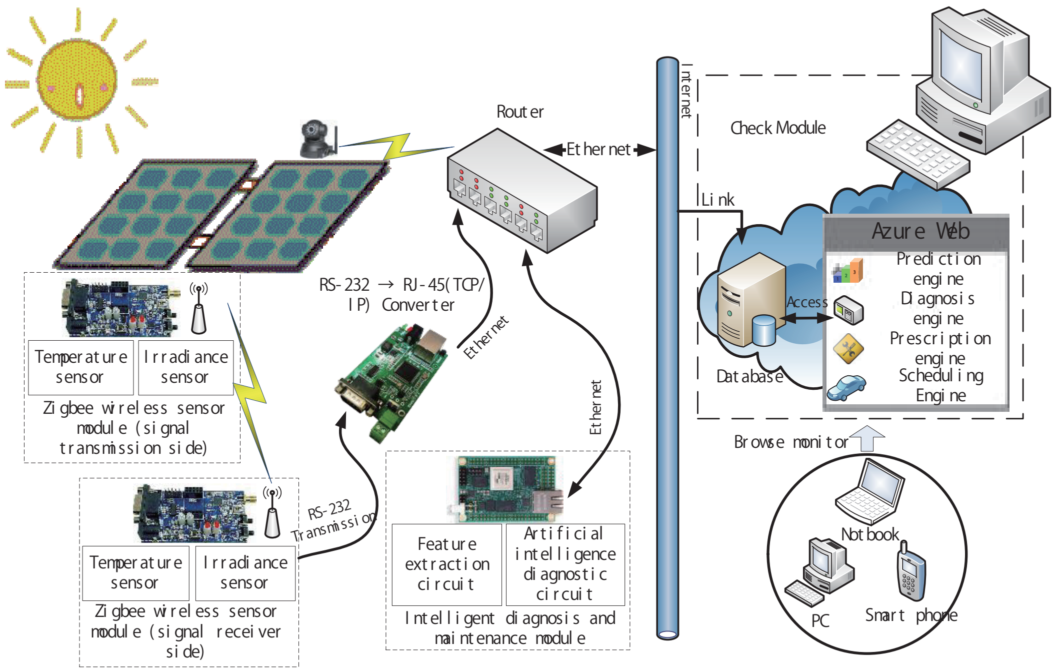

Fig. 1. (Color online) Architecture of maintenance scheduling for solar-energy-generating system.

2.3 Flowchart of maintenance scheduling for solar-energy-generating system

The flowchart of maintenance scheduling for the solar-energy-generating system is shown in Fig. 2. The intelligent diagnosis and maintenance system involves (1) data acquisition from the wireless sensors network, (2) feature extraction for reducing data, (3) intelligent computing on the embedded systems, and the (4) cloud database for data storage.

3. Intelligent Maintenance Scheduling System

3.1 Design of intelligent maintenance scheduling by PSO method

The lowest cost requirement is the target for the PSO method. The cost equations are Eqs. (1) and (2). The specifications of intelligent maintenance scheduling for the solar-energy-generating system are shown in Table 2.

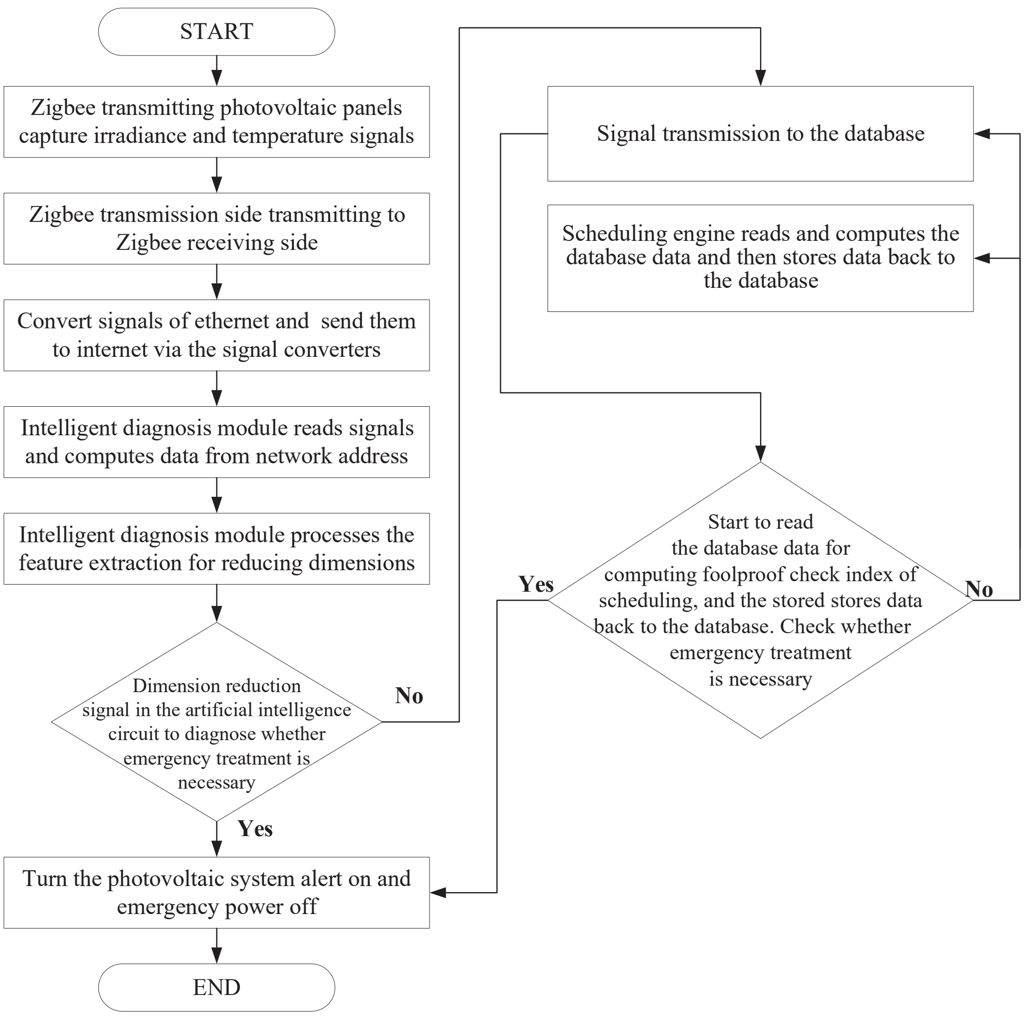

Fig. 2. Flowchart of maintenance scheduling for solar-energy-generating system.

$$PVC = \frac{PVBC}{\frac{PVK}{1000} \times 8\text{ (h)} \times 365\text{ (d)} \times 20\text{ (year)}} \tag{1}$$

$$IC = PVRC - PVC \tag{2}$$

As shown by Eq. (3), we can obtain *Pe* by calculating the variables in Table 3, namely, *Ppre* and *Pdc*. As shown by Eq. (4), *PVLC* is calculated from *Pe* and *IC*. *MT* is generated by the maintenance prescription engine of the solar-energy-generating system. All calculation results of PVRs' *RT* are shown in Table 4.

$$Pe = (Pdc - Ppre)^2 \tag{3}$$

$$PVLC = \frac{Pe}{1000} \times IC \tag{4}$$

As shown by Eq. (5), the model of the maintenance scheduling engine of the solar-energy-generating system was formulated using the variables in Table 1. Considering *RT*, *MT*, and *PL*, we

Table 2
Specifications of intelligent maintenance scheduling for solar-energy-generating system.

PVR	PVR1	PVR2	PVR3	…	PVR*n*−1	PVR*n*
PVBC (NT)	*PVBC*1	*PVBC*2	*PVBC*3	…	*PVBCn*−1	*PVBCn*
PVK (d/W)	*PVK*1	*PVK*2	*PVK*3	…	*PVKn*−1	*PVKn*
PVC (NT/kW)	*PVC*1	*PVC*2	*PVC*3	…	*PVCn*−1	*PVCn*
PVRC (NT/kW)			*PVRC*			
IC (NT/kW)	*IC*1	*IC*2	*IC*3	…	*ICn*−1	*ICn*

Table 3
Loss cost of solar-energy-generating system.

PVR	PVR1	PVR2	PVR3	…	PVR*n*−1	PVR*n*
Ppre (W)	*Ppre*1	*Ppre*2	*Ppre*3	…	*Ppren*−1	*Ppren*
Pdc (W)	*Pdc*1	*Pdc*2	*Pdc*3	…	*Pdcn*−1	*Pdcn*
Pe	*Pe*1	*Pe*2	*Pe*3	…	*Pen*−1	*Pen*
PVLC (NT/kW)	*PVLC*1	*PVLC*2	*PVLC*3	…	*PVLCn*−1	*PVLCn*
MT (h)	*MT*1	*MT*2	*MT*3	…	*MTn*−1	*MTn*

Table 4
Preparation time (*RT*).

PVR	PVR1	PVR2	PVR3	…	PVR*n*−1	PVR*n*
PVR1	0	*RT*(1,2)	*RT*(1,3)	…	*RT*(1,*n*−1)	*RT*(1,*n*)
PVR2	*RT*(2,1)	0	*RT*(2,3)	…	*RT*(2,*n*−1)	*RT*(2,*n*)
PVR3	*RT*(3,1)	*RT*(2,2)	0	…	*RT*(3,*n*−1)	*RT*(3,*n*)
...	...	...	...	0	…	...
PVR*n*−1	*RT*(*n*−1,1)	*RT*(*n*−1,2)	*RT*(*n*−1,3)	…	0	*RT*(*n*−1,*n*)
PVR*n*	*RT*(*n*,1)	*RT*(*n*,2)	*RT*(*n*,3)	…	*RT*(*n*,*n*−1)	0

obtain Eq. (5). The minimum cost of the maintenance schedule for the solar-energy-generating system is the target function for PSO. The optimal computing iteratively calculates the target function and limited conditions, and generates the results of optimal scheduling.

Target function = Minimum cost of photovoltaic system optimal maintenance scheduling:

$$MSC_{min} = f(RT, MT, PVLC) = \sum_{i}^{n} [(RT_{PVi} + MT_{PVi})(PL_{PVi} + PL_{PVi+1} + \ldots + PL_{PVn})]. \quad (5)$$

3.2 Implementation of intelligent maintenance scheduling by PSO method

In Fig. 3, the architecture of intelligent maintenance scheduling is shown. In Fig. 4, the flowchart of intelligent maintenance scheduling is shown.

4. Results and Discussions

Limits of intelligent maintenance scheduling by PSO method.

(1) The initial position is the same.

(2) The number of teams is limited (MTeam1, MTeam2, MTeam3, and MTeam4; maximum number = 4).

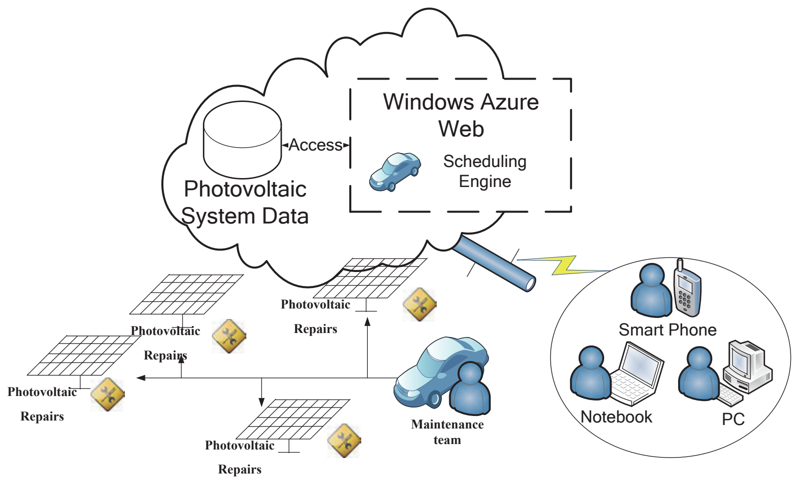

Fig. 3. (Color online) Architecture of intelligent maintenance scheduling.

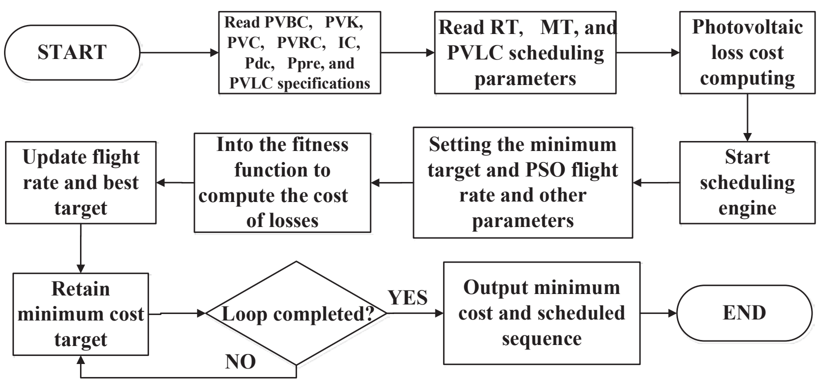

Fig. 4. Flowchart of intelligent maintenance scheduling.

(3) The number of solar-energy-generating stations is limited (PVR1, PVR2, PVR3, PVR4, ..., PVR9; maximum number = 9).
(4) The repair time from the maintenance prescription is limited.
(5) The team number of teams for one solar-energy-generating station is limited (maximum number = 1).
(6) No team can change during preparation.

$$\text{Target function} = \text{Minimum cost of photovoltaic system optimal maintenance scheduling} \quad (6)$$

The cost results of intelligent scheduling of maintenance prescription for the performance of the solar-energy-generating system by the PSO method are shown in Fig. 5. The top cost curve of order maintenance is also shown. The middle cost curve means the shortest preparation time for a priority maintenance. The bottom cost curve means optimized maintenance schedules. We can see the trend of cost curves in Fig. 5.

As shown in Table 5, in accordance with the minimum loss cost of the maintenance schedule, the maintenance team can get the optimal maintenance schedule of the solar-energy-generating system.

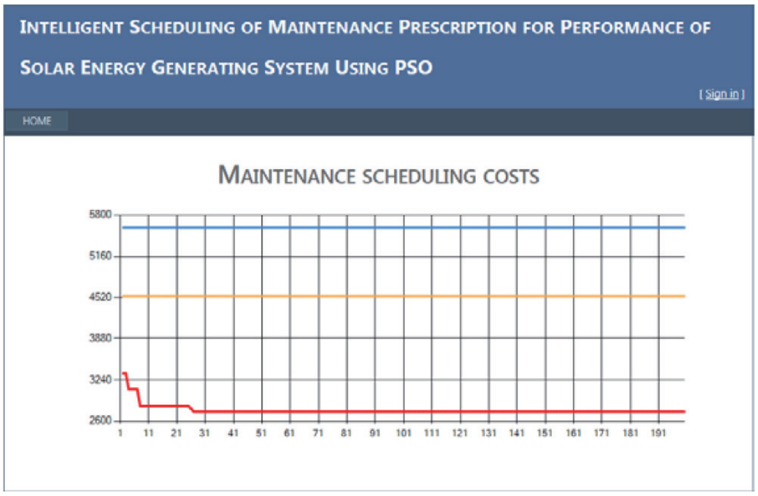

Fig. 5. (Color online) Cost results of intelligent maintenance scheduling of solar-energy-generating system by PSO method.

Table 5
Loss cost of the maintenance schedule.

Maintenance schedule		PVR		
1	PVR5	PVR3	PVR9	PVR8
2	PVR1	PVR2	PV4	PVR6
3	—	—	—	PVR7
Cost (NT)		2739		

As shown in Table 6, one team can only be assigned once for one solar-energy-generating station. In accordance with the maintenance schedule, work is assigned to the maintenance team. When a solar-energy-generating station is not scheduled for maintenance, it must wait in order.

As shown in Table 7, the lead time and maintenance time will be used to calculate the total time (*TT*) for nine solar-energy-generating stations in accordance with the degree of diagnostic questions to determine the work time for maintenance.

As shown in Fig. 6, the maintenance scheduling Gantt chart is generated at the cloud computing-based human–machine interface in accordance with the lead time. The maintenance time and the total time are shown in Table 7. It is easy to understand the working status of the maintenance teams.

Table 6
Maintenance schedule for the maintenance team.

MTeam		MTeam1	MTeam2	MTeam3	MTeam4
Maintenance schedule	1	PVR5	PVR3	PVR9	PVR8
	2	PVR1	PVR2	PVR4	PVR6
	3	—	—	—	PVR7

Table 7
Allocation table of maintenance team and working hours for solar-energy-generating system.

PVR (h)	PVR1 (h)	PVR2 (h)	PVR3 (h)	PVR4 (h)	PVR5 (h)	PVR6 (h)	PVR7 (h)	PVR8 (h)	PVR9 (h)
RT	10.1	12.9	0.6	14.8	0.4	7.7	11.4	1.4	2.7
MT	9.0	4.0	10.0	6.0	7.0	2.0	12.0	3.0	8.0
TT	19.1	5.7	14.9	12.5	7.4	4.0	17.7	4.4	24.6
MTeam	MTeam1	MTeam2	MTeam2	MTeam3	MTeam1	MTeam4	MTeam4	MTeam4	MTeam3

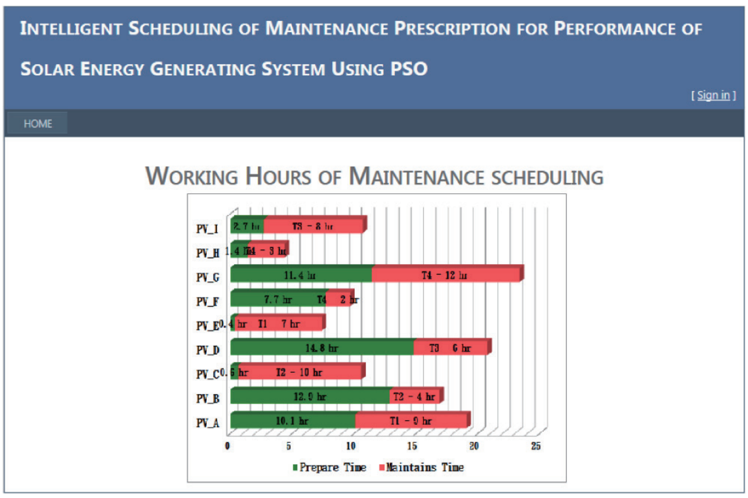

Fig. 6. (Color online) Maintenance scheduling Gantt chart.

5. Conclusions

For various uncertainties, the optimal solution of scheduling is considered. To reduce maintenance costs and improve maintenance efficiency, the intelligent scheduling system using the PSO method was built. In the scheduling model, the maintenance time and prework time were set to be the parameters of optimal computing, and the lowest cost was set to be the optimal target. This met both requirements of efficiency and lowest cost for the intelligent maintenance of the solar-energy-generating system.

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