Intelligent Control Scheme for Output Efficiency Improvement of Parallel Inverters

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Abstract: **Parallel inverters are often used for the interconnection of Renewable Energy Generation Systems (REGSs); however, the output efficiency using the conventional current-sharing control scheme is low at light loads. Therefore, an intelligent control scheme for output efficiency enhancement of parallel inverters is proposed in this paper. The proposed control scheme is based on the output efficiency curve of a single inverter and then an artificial-intelligence-based algorithm is used to find the optimal output efficiency of parallel inverters. The integration of the proposed control scheme into a Photovoltaic Generation System (PVGS) with a rated output power of 20kW interconnected by 10 inverters with rated output power of 2kW is simulated in this paper. Simulation results demonstrate the performance of the proposed intelligent control scheme in output efficiency improvement of parallel inverters at light loads.**

Keywords - Renewable Energy Generation System, Parallel Inverters, Artificial Intelligence, Optimal Output Efficiency

I. INTRODUCTION

Renewable Energy Generation Systems (REGSs) have continued to build up its share of the global electricity market. Two cost-competitiveness renewable power technologies - Photovoltaic Generation System (PVGS) and wind generation system have enabled new projects and therefore brought wind and PV much closer to full competitiveness with fossil fuel alternatives. The cumulative capacity of installed PVGSs worldwide was around 138GW until the end of 2013 and approximately 160TWh of electricity is generated each year. The performance of renewable energy investments in 2014 were arguably more impressive than that in 2013, because capital costs, particularly in PV generation, fell sharply. Therefore, each billion dollars added up to more MW of capacity than it did in the earlier year. With the sharply reduced cost of PVGSs, a record amount of PVGS capacity was reached from 39GW in 2013 to 46GW in 2014 and is expected that at least a 4-5% increase in PVGS market growth can be reached in the next few years [1-2]. The total installed capacity of worldwide PVGSs is about 184GW until the end of 2014. If 1% average output power enhancement can be achieved, an extra maximum 1.84GWh can be harvested from worldwide PVGSs hourly. Therefore, enhancing the output power of PVGS cannot only increase the practicability of PVGS but also make the PV industry more competitive.

Due to the limited capacity of a single inverter, parallel inverters are often used for the interconnection of PVGSs. Therefore, one of the most commonly-used methodologies used to increase the output power of PVGSs is to enhance the output efficiency of parallel inverters. A variety of control strategies, especially the droop control and current-sharing control, have been proposed for parallel inverter operation [3]-[15]. The current-sharing control is one of the commonly-used control strategies for parallel inverters; however, the output efficiency is low at light loads. Therefore, an intelligent control scheme for output efficiency enhancement of parallel inverters at light loads is proposed in this paper. The proposed control scheme is based on the output efficiency curve of a single inverter, and then an artificial-intelligence-based algorithm is used to find the optimal output efficiency of parallel inverters. The integration of the proposed control scheme into a PVGS with a rated output power of 20kW interconnected by 10 inverters with rated power of 2kW is simulated in this paper. Simulation results demonstrate that the proposed intelligent control scheme can effectively enhance the output efficiency of parallel inverters at light loads and increase the electrical energy output of PVGS.

II. BASIC CONCEPTS OF PARALLEL INVERTERS

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Fig. 1 illustrates one of control block diagrams for the current-sharing control of parallel inverters. The rated power of the parallel inverters must be added up to the peak power of the load. The current-programming control center provides the current reference for each parallel inverter. i_i , V_L and V_L^r as illustrated in Fig. 1 are the measured current for inverter i, measured voltage and voltage reference, respectively. i_i^r and i_L are the current reference for inverter i and total output current of parallel inverters, respectively. N is the number of parallel inverters. The average current-sharing control is commonly used for parallel inverters with the same rated output power. Using the output efficiency of an inverter with rated output power 2kW acquired from the single-phase inverter implemented in this paper as an example, the output efficiency at the loads between 0.2kW to 1.6kW supplied by a single inverter and two parallel inverters is shown in Fig. 2. From Fig. 2, it can be clearly observed that the output efficiency of two parallel inverters operated by average current-sharing control at light loads (between 0.2kW to 1.6kW) is lower than the output efficiency whilst being operated by a single inverter.

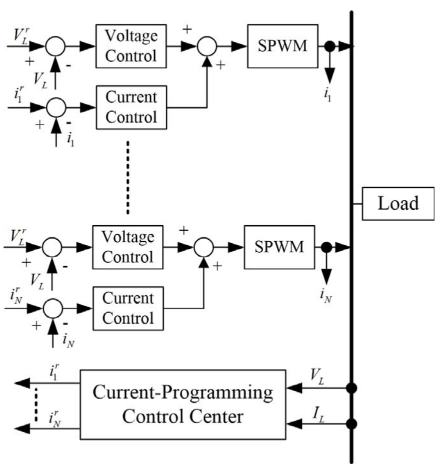


Fig. 1: One of Control Block Diagrams for Current-Sharing Control

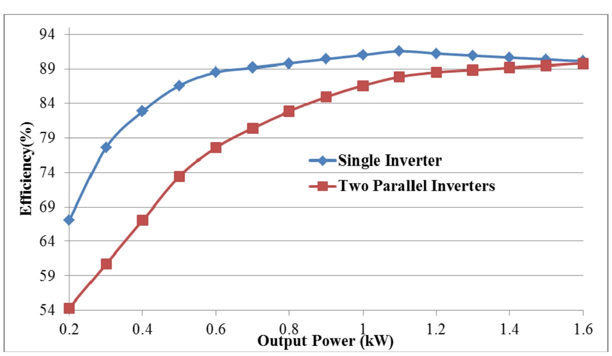


Fig. 2: Output Efficiency at Light Loads

The shortcomings of conventional current-sharing control for parallel inverters at light loads greatly affect the output power of PVGS, since about 25% and 45% of the sunshine hours for the summer day and winter day, respectively, the power outputs of PVGS are less than 30% of its installed capacity. Likewise, from Fig. 2, it can be observed that if some of the parallel inverters at the light loads can be switched off or the current reference of each parallel inverter can be adjusted, then the output efficiency of parallel inverters at the light loads can be effectively enhanced and more energy can be harvested from PVGSs. Therefore, an intelligent control scheme, used to find the current reference of each parallel inverter, is proposed in this paper.

III. Proposed Intelligent Control scheme

An intelligent control scheme for output efficiency enhancement of parallel inverters at light loads is proposed in this paper. The proposed control scheme is based on the output efficiency curve of a single inverter, where an artificial-intelligence-based algorithm is used to find the current reference of each parallel inverter to achieve the overall optimal output efficiency of the parallel inverters. The output efficiency of parallel inverters can be expressed as

$$Eff^{PIS} = \frac{\sum_{i=1}^{N}(P_i^{out})}{\sum_{i=1}^{N}(P_i^{in})} = \frac{\sum_{i=1}^{N}(P_i^{out})}{\sum_{i=1}^{N}\left(\frac{P_i^{out}}{F_i^{eff}(P_i^{out})}\right)} \quad (1)$$

where P_i^{in} and P_i^{out} are the input and output powers of inverter i respectively and Eff^{PIS} is the output efficiency of parallel inverters. A higher Eff^{PIS} value indicates a high output efficiency where a higher amount of output power can be obtained from the same input power. $F_i^{eff}(\bullet)$ is the output efficiency function of inverter i.

The objective function and constraints of the proposed intelligent control scheme can then be expressed as

$$\max \ Eff^{PIS} \quad (2a)$$

s.t.

$$\sum_{i=1}^{N} P_i^{out} = P_L \quad (2b)$$

$$0 \le P_i^{out} \le P_i^{rated} \quad i = 1 \sim N \quad (2c)$$

where P_L is the total output power of the parallel inverters and P_i^{rated} is the rated power of inverter i.

Eq. (2) can be used to determine the number of inverters in parallel and the current reference of each parallel inverter to achieve the optimal output efficiency at light loads. The output efficiency function in (2) can be obtained from the output efficiency curve of an inverter. For example, a piecewise curve fitting, which divides the output efficiency curve of an inverter into several quadratic polynomial functions as written in (3), can be used to establish the output efficiency function.

$$F_i^{eff}(P_i^{out}) = \begin{cases} a_{i,1}P_i^{out^2} + b_{i,1}P_i^{out} + c_{i,1} & 0 < P_i^{out} \le P_{i,1}^{out} \\ a_{i,2}P_i^{out^2} + b_{i,2}P_i^{out} + c_{i,2} & P_{i,1}^{out} < P_i^{out} \le P_{i,2}^{out} \\ \vdots & \\ a_{i,m}P_i^{out^2} + b_{i.m}P_i^{out} + c_{i,m} & P_{i,m}^{out} < P_i^{out} \le P_i^{\max} \end{cases} \quad (3)$$

where $a_{i,x}$, $b_{i,x}$ and $c_{i,x}$ are parameters for the quadratic polynomial function between input power ($P_{i,x-1}^{out}$) and output power ($P_{i,x}^{out}$) of inverter i, respectively.

The optimization problem as formulated in (2) can be solved by artificial-intelligence-based algorithms. Particle Swarm Optimization (PSO) algorithms, inspired by flocking and schooling patterns of birds and fish, are one of the most commonly-used artificial-intelligence-based algorithms in solving optimization problems and more been applied for many engineering problems [16-19]. A commonly-used PSO-based algorithm is implemented in this paper to find the current reference of each parallel inverter to achieve the optimal output efficiency of parallel inverters. The main steps of the PSO-based algorithm used in solving the proposed intelligent control scheme are briefly summarized as:

Step#1: Initialize particles: Each particle is initialized by randomly selection from the entire set of possible control variables, i.e. search space. The particle m for the proposed intelligent control scheme can be expressed as

$$\mathbf{x}_{m,n}^P = \begin{pmatrix} P_{m,1}^{out} & P_{m,2}^{out} & \cdots & P_{m,N-2}^{out} & P_{m,N-1}^{out} \end{pmatrix}_n^T \quad m = 1 \cdots N_P \quad (4)$$

where $\mathbf{x}_{m,n}^P$ is the position vector for particle m at iteration n and $P_{m,i}^{out}$ is the output power of inverter i in particle m and N_P is the number of particles. $\mathbf{x}_{m,0}^P$, the position vector for particle m at iteration 0, can be generated at random.

In addition, the velocity, $\mathbf{v}_{m,n}^P$, for particle m at iteration n can be expressed as

$$\mathbf{v}_{m,n}^P = \begin{pmatrix} v_{m,1} & v_{m,2} & \cdots & v_{m,N-2} & v_{m,N-1} \end{pmatrix}_n^T \quad m = 1 \cdots N_P \quad (5)$$

Step#2: Calculate fitness value: Each particle is assigned a fitness value based on the position vector of this particle as shown below:

$$fitness = Eff^{PIS}(\mathbf{x}_{m,n}^P) + \sum_{i=1}^{N} PF_{INV} \quad (6)$$

where PF_{INV} is the penalty factor when constraint (2c) is violated.

Step#3: Evaluate $\mathbf{pbest}_m$ and $\mathbf{gbest}$: $\mathbf{pbest}_m$ is the position vector for particle m keeping its own best fitness value. $\mathbf{gbest}$ is the position vector of best $\mathbf{pbest}_m$.

Step#4: Update position and velocity vectors: The particle's exploration at iteration n+1 is influenced by the vectors of its previous velocity ($\mathbf{v}_{m,n}^P$), its previous best position ($\mathbf{pbest}_m$) and the global best position in the swarm ($\mathbf{gbest}$). The position and velocity vectors of each particle can be updated by

$$\mathbf{v}_{m,n+1}^P = c_0\mathbf{v}_{m,n}^P + c_1\varphi_1(\mathbf{pbest}_m - \mathbf{x}_{m,n}^P) + c_2\varphi_2(\mathbf{gbest} - \mathbf{x}_{m,n}^P) \quad (7a)$$

$$\mathbf{x}_{m,n+1}^P = \mathbf{x}_{m,n}^P + \mathbf{v}_{m,n+1}^P \quad (7b)$$

where c_0 is inertia weighting. c_1 and c_2 represent the individuality and sociality coefficient respectively. φ_1 and φ_2 are random numbers in the range (0, 1).

Step#5: Stopping criterion: Steps 2-3 for each iteration are repeated until the maximum number of iterations is reached.

The parameters for the PSO-based algorithm used in the this paper are N_P: 50, PF_{INV}: -100, c_0: 0.5 , c_1: 1 , c_2: 1.5, with a maximum iteration number: 200.

IV. Simulation Results and Discussions

Simulation results comparing the proposed intelligent control scheme and with an average current-sharing control method are used to demonstrate the performance of the proposed intelligent control scheme. Fig. 3 shows the output efficiency curve of an inverter with a rated output power of 2kW. The output efficiency curve as illustrated in Fig. 3 can be divided into 4 segments. The mathematical formula of piecewise curve fitting using several quadratic polynomials can be written as

$$F_i^{eff}(P_i^{out}) = \begin{cases} 127.18 \ast P_i^{out} + 41.62 & 0 < P_i^{out} \le 0.26 \\ (-77.13) \ast {P_i^{out}}^2 + 106.67 \ast P_i^{out} + 52.53 & 0.26 < P_i^{out} \le 0.57 \\ (-0.79) \ast {P_i^{out}}^2 + 7.41 \ast P_i^{out} + 84.37 & 0.57 < P_i^{out} \le 1.10 \\ (1.29) \ast {P_i^{out}}^2 + (-6.33) \ast P_i^{out} + 96.94 & 1.10 < P_i^{out} \le 2.0 \end{cases} \quad (8)$$

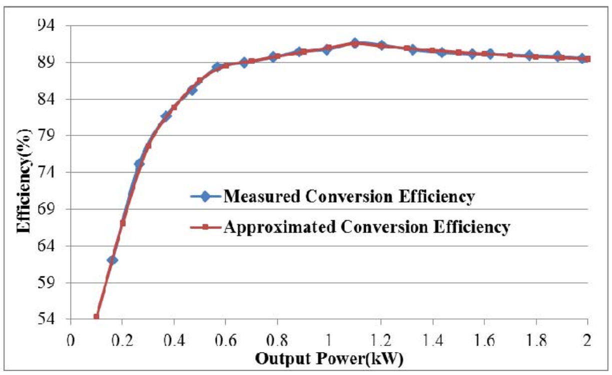


Fig. 3: Output Efficiency Curve of a Rated 2kW Inverter

Two inverters are used to validate the performance of the proposed intelligent control scheme for parallel inverters. Fig. 4 shows the simulated output efficiency curves for the proposed intelligent control scheme and average current-sharing control. Table I listed the output power of each parallel inverter under different total output powers. From Fig. 4 and Table I, it can be clearly observed that the output efficiency can be effectively enhanced while the load is less than 1.6kW. When the load is larger than 1.6kW, the output efficiencies of the proposed intelligent control scheme and average current-sharing control are almost identical.

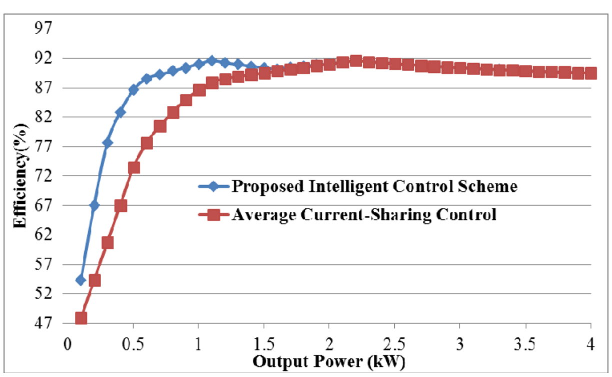


Fig. 4: Simulated Output Efficiency Curves

TABLE I

OUTPUT POWER OF EACH PARALLEL INVERTER

P_L (kW)	$P_1^{out,r}$ (kW)	$P_2^{out,r}$ (kW)	P_L (kW)	$P_1^{out,r}$ (kW)	$P_2^{out,r}$ (kW)
0.2	0.2	0	2.2	1.1	1.1
0.4	0.4	0	2.4	1.2	1.2
0.6	0.6	0	2.6	1.3	1.3
0.8	0.8	0	2.8	1.4	1.4
1.0	1	0	3.0	1.5	1.5
1.2	1.2	0	3.2	1.6	1.6
1.4	1.4	0	3.4	1.7	1.7
1.6	1.6	0	3.6	1.8	1.8
1.8	1.1	0.7	3.8	1.9	1.9
2.0	1.1	0.9	4.0	2	2

The integration of the proposed control scheme into a PVGS with a rated output power of 20kW interconnected by 10 inverters with rated output power of 2kW is also simulated in this paper. PVGSs have intermittent output characteristics associated with the random phenomenon of solar irradiance. Refs. [20-21] shows that a Beta probability density function can be effectively used to model solar irradiance. The output power of PV panels is dependent on the solar irradiance and ambient temperature of the site as well as the parameters of the PV panels used. The output power of PV panels in a PVGS, i.e. the input power of parallel inverters, can be simulated by [22]. Table II lists the mean and standard deviation of hourly solar irradiance during summer and winter daytime acquired from the Taiwan Weather Bureau. Fig. 5 shows the cumulative probabilities for the output power of PV panels calculated based on the solar irradiances in Table II. It can be observed from Fig. 5 that about 45% and 25% of the sunshine hours for the winter and summer days, respectively, the power outputs of PV panels in the 20kW PVGS are less than 30% (about 6kW) of its installed capacity.

Fig. 6 illustrates the simulated output efficiency curves of the proposed intelligent control scheme and average current-sharing control for the 10 parallel inverters. The output energy enhancement per hour based on the proposed intelligent control scheme and average current-sharing control can be calculated by

$$OEE_h = \frac{(PVGS_{kWh,h}^{SCS} - PVGS_{kWh,h}^{ACC})}{PVGS_{kWh,h}^{ACC}} \ast 100\% \quad (9)$$

where OEE_h is percentage of output energy enhancement for PVGS at hour h. $PVGS_{kWh,h}^{SCS}$ and $PVGS_{kWh,h}^{ACC}$ are the output energies in kWh at hour h operated by the proposed intelligent control scheme and average current-sharing control, respectively.

TABLE II
MEAN AND STANDARD DEVIATION OF SOLAR IRRADIANCES

	Summer (kW/m^2)		Winter (kW/m^2)	
Hour	Mean	Standard Deviation	Mean	Standard Deviation
8	0.237	0.056	0.067	0.042
9	0.400	0.087	0.205	0.082
10	0.523	0.127	0.337	0.120
11	0.632	0.156	0.443	0.142
12	0.663	0.162	0.516	0.161
13	0.657	0.164	0.539	0.158
14	0.612	0.147	0.479	0.151
15	0.497	0.143	0.378	0.124
16	0.349	0.116	0.241	0.085
17	0.203	0.081	0.087	0.061

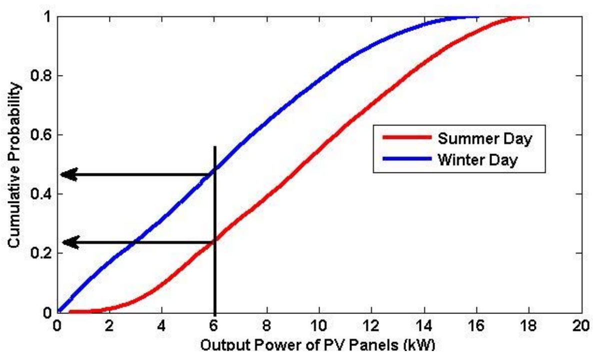


Fig. 5: Cumulative Probabilities for the Output Power of PV Panels

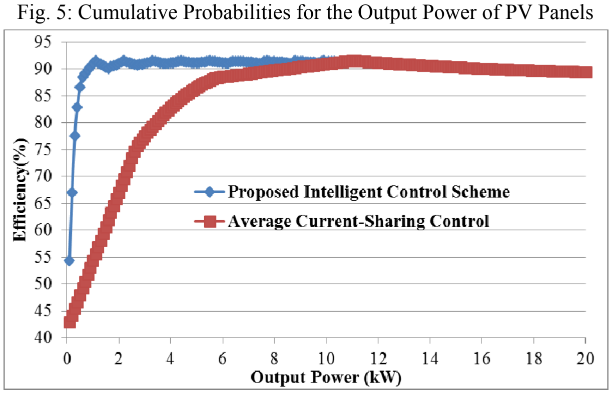
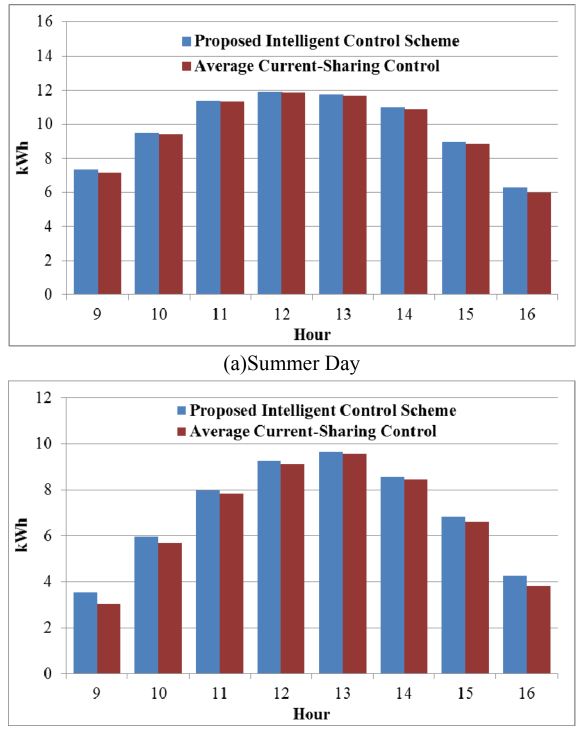


Fig. 6: Simulated Output Efficiency Curves for 20kW PVGS

Fig. 7 shows the output energies per hour for the parallel inverters in the 20kW PVGS operated by the proposed intelligent control scheme and average current-sharing control. Fig. 8 illustrates the percentage of output energy enhancement calculated by (9) for the 20kW PVGS. From Fig. 8, it can be observed that the maximum output energy enhancements are about 4.2% and 16.6% for the summer and winter days, respectively. Simulation results demonstrate that the proposed intelligent control scheme can effectively increase the electrical energy output of PVGS. If average output power enhancement can be achieved, more energy can be harvested from worldwide PVGSs hourly; therefore, the proposed intelligent control scheme cannot only increase the practicability of PVGSs but also make the PV industry more competitive.



(a)Summer Day

(b)Winter Day

Fig. 7: Performance Comparison for the 20kW PVGS

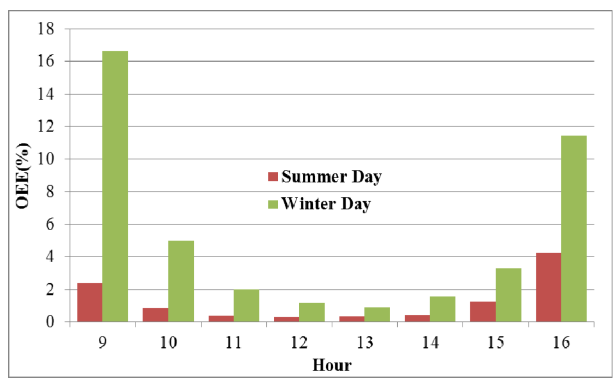


Fig. 8: Percentages of Output Energy Enhancement

V. CONCLUSIONS

The current-sharing control is the commonly-used operating strategy for parallel inverters; however, the output efficiency is low at light loads. An intelligent control scheme for parallel inverters was proposed in this paper to effectively enhance the output efficiency at the light loads. Simulation results demonstrated the performance of the proposed intelligent control scheme for the output efficiency enhancement of parallel inverters at light loads. The proposed intelligent control scheme cannot only increase the practicability of PVGS but also make the PV industry more competitive.

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