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Load Dispatching Control of Multiple-Parallel-Converters Rectifier to Maximize Conversion Efficiency

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Abstract – In the context of increasing electric energy consumption in a data center, energy efficiency improvement is strongly emphasized. In a data center, electric energy is largely consumed by DC power supply system, which is based on a rectifier composed by multiple parallel converters. Therefore, rectifier efficiency must be improved for minimizing loss of DC power supply system. Rectifier efficiency can be modulated by load allocation to converters because converter efficiency depends on input AC power. In this paper, we propose a new control method to maximize rectifier efficiency. The method can control load allocation to converters by introducing active power converter control scheme and start-and-stop of converters. In order to illustrate optimal load allocations in a rectifier, a maximization problem of rectifier efficiency is formulated as a nonlinear optimization one. The problem is solved by Lagrangian relaxation method and the computation results provide the validity of proposed method.

Keywords: Data center, DC power supply, Energy efficiency, Load allocation, Parallel converters

1. Introduction

Data centers play an important role to maintain modern ICT societies, so that the number is rapidly growing. Electric energy consumption by data centers in the world reached 1.3% of all electricity use in 2010 [1]. The growth in electric energy consumption emphasizes importance of the further energy saving in data centers. In a recent data center, electric energy is mainly consumed by ICT devices, air conditioners and a DC power supply system [2]. And strategies for improving the electric energy efficiency of data center are studied in each section. For example, server virtualization is a valid approach for decreasing the electricity consumption of ICT devices [3]. And also, the method to cut electricity use of air conditioner by using outside air of the data center is studied [4].

The DC power supply system has a role of power conversion and stable power supply in a data center, so the system includes converters and batteries, whose energy efficiency depends on state of operation. Therefore, the electric power conversion efficiency of the system can be improved by advancement of control system.

The DC power supply system is based on a rectifier, which is composed of multiple parallel converters from the viewpoint of power supply reliability. Therefore the efficiency of the system is determined by efficiency of individual converter. Since the converter efficiency depends on the amount of converted power, the efficiency of the system depends on load allocation to converters in a rectifier [5]. In a conventional rectifier control method, the load allocation is not controllable for a load level and so the efficiency of the system is not variable.

In this paper, at first, a new rectifier control method which improve rectifier efficiency. The method can control load allocation in a rectifier by introducing active power converter control scheme and start-and-stop of converters. Next, in order to find optimal load allocation which maximizes the rectifier efficiency, an efficiency maximization problem is formulated as a nonlinear optimization one. The problem is solved by the Lagrangian relaxation method and the computation result shows that proposed method is valid for maximizing rectifier efficiency.

2. Strategy for Improving the Rectifier Efficiency

2.1 Conventional control method of a rectifier

Fig. 1 shows configuration of DC power supply system in a data center. It is composed of multiple three phase PWM converters which have same specific. Respective converters are controlled by vector control.

In this section, a simple rectifier composed of two converters as shown in Fig. 2 is used to explain rectifier control scheme. Under the conventional control scheme, Conv#1 and Conv#2 regulate DC voltage at a specified level. This control scheme of a converter is referred as DC voltage regulation (DCVR) in this paper. Both converters control DC voltage E_{dc}, so that switching patterns of both

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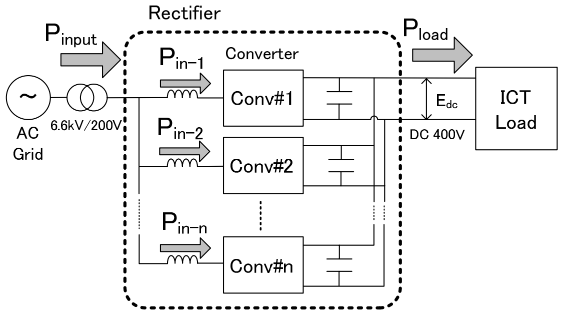

Fig. 1. Configuration of a rectifier [2]

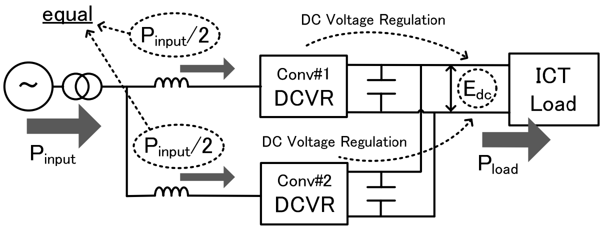

Fig. 2. Conventional control method of a rectifier

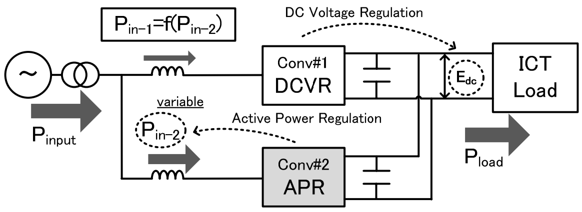

Fig. 3. Proposed control method of a rectifier

converters are same. Therefore, circuit configurations and impedances of both converters are same at any time and they convert the same amount of power $P_{input}/2$ [kW]. The load allocation is unique with respect to a load level [kW]. This means that the conventional control scheme allocates total load P_{load} equally to each converter and cannot change the load allocation and the rectifier efficiency.

2.2 Proposed method for load dispatching control

In order to control load allocation, it is necessary to adopt active power regulation (APR) as converter control scheme. APR can control the amount of input AC power delivered to each converter but cannot control DC voltage. If all converters are operated under APR, DC voltage cannot be maintained at appropriate levels and the DC power supply system cannot keep their stable operation.

A new control method proposed in this paper is to maintain DC voltage by DCVR converters and to control load allocation by APR converters at the same time. Fig.3 shows architecture of the proposed method. Conv#1 and Conv#2 are operated under DCVR and APR, respectively. Conv#1 keeps DC voltage at specified level and assures stable electric power supply to ICT loads. When Conv#2 determines input AC power $P_{in\text{-}2}$ [kW], Conv#1 converts the difference $P_{in\text{-}1}$ between total input P_{input} and $P_{in\text{-}2}$ [kW]. Since $P_{in\text{-}2}$ is controllable with Conv#2, $P_{in\text{-}1}$ is also variable. That is, the proposed method can change load allocation to converters of a rectifier. In addition, start-and-stop control of converters is included in the proposed method.

3. Rectifier Efficiency Maximization by Proposed Method

3.1 Optimization problem to determine efficient load allocation

Since a rectifier efficiency depends on load allocation to multiple converters, it is necessary to find the optimal load allocation. The optimal allocation, which is referred as efficient load allocation in this paper, can be obtained as a solution of the following nonlinear optimization problem.

Objective:

$$\min_{P_{in}} \; P_{input} = \sum_{i=1}^{n} P_{in-i} \tag{1}$$

Subject to:

- Constraints for input AC power

$$P_{lower-i} - P_{in-i} \le 0 \tag{2}$$

$$P_{in-i} - P_{upper-i} \le 0 \tag{3}$$

- Constraints of supply-demand balance

$$P_{ouput} = \sum_{i=1}^{n} \left\{ P_{in-i} \frac{\eta_i \left(P_{in-i} \right)}{100} \right\} = P_{load} \tag{4}$$

$$\boldsymbol{P_{in}} = \left[P_{in-1} \;\; P_{in-2} \;\; \cdots \;\; P_{in-n} \right]^T \ge \boldsymbol{0} \tag{5}$$

where

P_{in-i} [kW]: input power to Converter #i
$P_{lower-i}$ [kW]: lower limit of input power to Converter #i
$P_{upper-i}$ [kW]: upper limit of input power to Converter #i
$\eta_i \left(P_{in-i} \right)$ [%] : efficiency of Converter #i
P_{load} [kW]: power of ICT load

The objective function of (1) is minimization of total input AC power of a rectifier under a required constant load P_{load}. This formulation corresponds to maximizing rectifier efficiency.

3.2 Solution for the optimization problem

The problem formulated in the previous section is nonlinear optimization one, so that it is difficult to solve it without any transformation. Therefore, by applying Lagrangian relaxation method to the problem, it is transformed to unconstrained optimization problem as in (6).

Objective

$$\max_{\lambda\geq 0}\min_{P_{in}} \; P_{input}+\sum_{i=1}^{n}\left\{\lambda_{i1}\left(P_{lower-i}-P_{in-i}\right)+\lambda_{i2}\left(P_{in-i}-P_{upper-i}\right)\right\}+\mu\left(P_{output}-P_{load}\right) \tag{6}$$

Lagrange multiplier

λ_{i1} : the multiplier for lower limit of input power
λ_{i2} : the multiplier for upper limit of input power
μ : the multiplier for supply-demand balance

This problem is solved as follows. At the first step, the objective is minimized in terms of input AC power of converters P_{in-i} by Lagrange's method of undetermined multipliers. At the second step, the objective is maximized in terms of Lagrange multipliers λ_{i1}, λ_{i2} by penalty function method. By repeating these two steps, the solution is converged to optimum one which maximizes rectifier efficiency.

As mentioned later, the converter efficiency $\eta_i\left(P_{in-i}\right)$ is represented as segmented linear functions of input AC power, $\eta^{(j)}\left(P_{in-i}\right)$. As a result, the abovementioned optimization problem becomes a complex combinatorial optimization problem with respect to the functions $\eta^{(j)}\left(P_{in-i}\right)$. Therefore, the optimum solution is searched according to the algorithm as shown in Fig. 4.

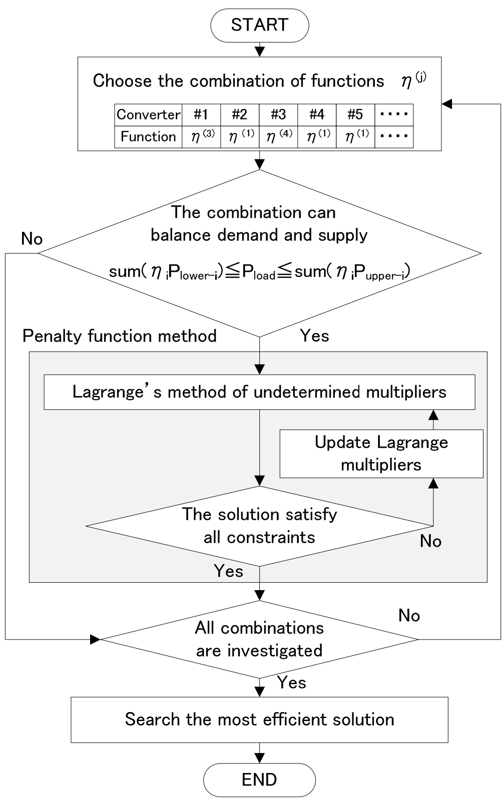

Fig. 4. Procedure for the optimization problem calculation

4. Validity Confirmation of Proposed Method

In this section, at first, a rectifier used in an actual data center is modeled. And then the validity of the proposed rectifier control is checked by solving the load allocation problem with respect to the model.

4.1 A rectifier model

The rectifier model used for the validity check is composed of seven converters. The rated power of individual converter is 15 kW and the converters are connected each other as shown in Fig. 1. Fig. 5 shows the efficiency characteristic curve $\eta_i\left(P_{in-i}\right)$ of an actual converter [6], which is represented by 12 measurements and 11 segments $\eta^{(j)}\left(P_{in-i}\right)$ (j=1,⋯,11). The converter is designed so that conversion efficiency peaks at about 50% of the rated power. This is because average load level of data center is about 50% of installed capacity [7].

4.2 Computation result of efficient load allocation

Table 1 shows the load allocations maximizing rectifier efficiencies at several ICT load levels. In the table, the efficiencies and load allocations in conventional rectifier control are also shown.

The efficiency of proposed control method rises up in any load levels except for load of 60kW. The efficient load allocations of all the load levels indicate that many converters are operated at the load of about 8.8 kW which maximizes the efficiency of each converter. Therefore, the rectifier efficiency can be maximized by adjusting the load allocation so as to increase the number of converter operated in maximum efficiency. In the case of 60 kW loads, all converters are operated at maximum efficiency load level 8.8 kW in the conventional control, so that the proposed control does not need to change the load allocation.

In the case of light loads, 30 kW and 40 kW, the rectifier efficiencies are improved widely. This improvement depends on the number of operated converters. In the conventional control, a total load on the rectifier is

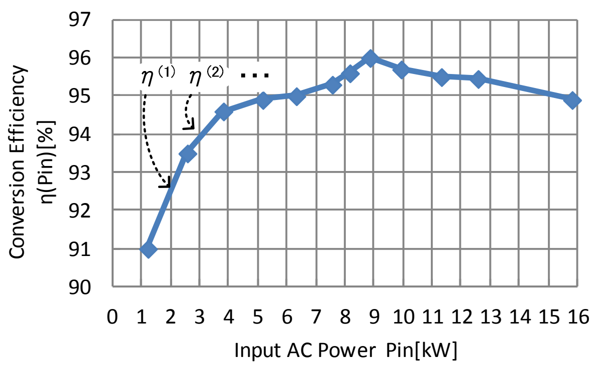

Fig. 5. Efficiency characteristic of a converter [6]

Table 1. Optimal load allocation maximizing rectifier efficiency

ICT Load		30kW		40kW		50kW		60kW		70kW	
Control Method		Convention	Proposed	Convention	Proposed	Convention	Proposed	Convention	Proposed	Convention	Proposed
Efficiency[%] (Advancement)		94.758	**95.771 (+1.013)**	94.474	**95.849 (+1.375)**	95.292	**95.909 (+0.617)**	**95.979**	**95.979 (+0.0)**	95.623	**95.716 (+0.093)**
Load allocation[kW]	Conv#1	4.523	**9.079**	6.017	**8.855**	7.496	**8.801**	**8.931**	**8.931**	10.458	12.572
	Conv#2	4.523	**9.079**	6.017	**8.855**	7.496	**8.801**	**8.931**	**8.931**	10.458	12.572
	Conv#3	4.523	**9.079**	6.017	**8.855**	7.496	**8.801**	**8.931**	**8.931**	10.458	12.572
	Conv#4	4.523	4.088	6.017	**8.855**	7.496	**8.801**	**8.931**	**8.931**	10.458	**8.854**
	Conv#5	4.523		6.017	6.313	7.496	**8.801**	**8.931**	**8.931**	10.458	**8.854**
	Conv#6	4.523		6.017		7.496	8.125	**8.931**	**8.931**	10.458	**8.854**
	Conv#7	4.523		6.017		7.496		**8.931**	**8.931**	10.458	**8.854**

Table 2. Assignment of converter control scheme in the case of 30 kW load

	Power	Control scheme combination			
	[kW]	#1	#2	#3	#4
Conv#1	9.079	APR	DCVR	DCVR	DCVR
Conv#2	9.079	APR	APR	DCVR	DCVR
Conv#3	9.079	APR	APR	APR	DCVR
Conv#4	4.088	DCVR	APR	APR	APR

allocated equally to all seven converters, so that each converter must be operated at a lower efficiency load level.

On the other hand, the proposed control method operates a part of the converters so as to maximize the rectifier efficiency.

To implement the optimal load allocation of rectifier, which converters should be controlled in DCVR and the others are in APR must be determined suitably. For example, in the case of 30 kW load in Table 1, since there are four active converters in the optimal load allocation, the number of simple combinations of DCVR converter and APR one is 2^4=16. However, since at least one DCVR converter is needed to maintain the DC voltage in the data center, all converters could not be operated in APR. And also, DCVR converters supply the same amount of power. If Conv#4 supplying power of 4.088 kW is operated in DCVR, the other converters supplying 9.079 kW cannot be operated in DCVR. Therefore, control scheme assignment shown in Table 2 can be implemented if Conv#1, #2 and #3 which convert same power of 9.079 kW are not distinguished.

Control scheme combination #1 and #2 have only one DCVR converter respectively. When the DCVR converter is broken down and stopped, the rectifier can't keep their operation. On the other hand, combination #3 and #4 have more than two DCVR converters. That is, if one of DCVR converters is stopped, the rectifier can keep their operation by the other DCVR converters maintain DC voltage. Then, from the viewpoint of reliability, many converters should be operated in DCVR. For this reason, control scheme combination #4, which has the largest number of DCVR converters, makes most reliable operation of the rectifier in the case. In the other load levels, the combination of DCVR and APR can be determined in the same way.

5. Conclusion

This paper proposes a new control method of multiple-parallel-converters rectifier which enables to enhance its conversion efficiency by modulating load allocation to converters. In order to find efficient load allocation, rectifier efficiency maximization problem is formulated and its solution is developed. The result of numerical computation shows that the proposed method is valid in all of load levels. And also it is indicated that the rectifier efficiency is improved by increasing the number of converters which is operated in maximum efficiency.

References

[1] Jonathan G. Koomy: "Growth in Data Center Electricity use 2005 to 2010", Analytics Press (2011).

[2] Akiyoshi Fukui, Takashi Takeda, Keiichi Hirose, and Mikio Yamasaki : "HVDC Power Distribution Systems for Telecom Sites and Data Centers", Proc. of IEEE IPEC 2010, pp.874-880 (2010).

[3] IBM : "Server Virtualization"

[4] Kunikazu Tsuda, Shunichi Tano, Junko Ichino, "Lower Data Center Power Consumption through Use of the Climate Characteristics of Cold Regions and Interregional Energy Integration", Proc. of IEEE PIC 2010, pp.1298-1304 (2010).

[5] Dai Orihara, Hiroumi Saitoh, Yuji Higuchi and Tadatoshi Babasaki," A Study on Efficiency Maximization of DC Power Supply System by Using Active Power Control," IEICE Technical Report, Vol. 112, No.396, pp. 135-140, Jan.2013. (in Japanese)

[6] Akira Matsumoto, Akiyoshi Fukui, Takashi Takeda, Keiichi Hirose and Mikio Yamasaki, "Development of 400 Vdc Power Distribution System and 400 Vdc Output Rectifier," Proc. of IEEE INTELEC 2009, pp. 1-5, 2009.

[7] Symantec: "State of the Data Center – Global Second Annual Report 2008", pp.10-11.

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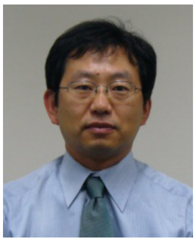

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