Journal of Southeast University (English Edition) Vol. 26, No. 3, pp. 415 – 420 Sept. 2010 ISSN 1003—7985

EDLC charging performance for microgrid applications

Xu Qingshan Bian Haihong Zhao Weiran

(Engineering Research Center of Motion Control of Ministry of Education, Southeast University, Nanjing 210096, China)

Abstract: In order to review storage performance of the electric double layer capacitor (EDLC) in microgrid applications, charging time and storage efficiency issues are mainly studied aiming at three different charging modes, including the constant voltage charging mode (CVCM), the constant current charging mode (CCCM) and the constant power charging mode (CPCM), based on the practical EDLC product. Numerical calculation methods are presented for different charging modes, and the charging efficiency is also reviewed with strict mathematical deductions, which is validated to be accurate enough and applicable through a simple case with the PV/EDLC system illustration. Finally, trade-off problems between charging time and energy loss are also studied. Research results show that the CPCM is more suitable for microgrid networks compared with the traditional constant-voltage and constant-current charging modes. The hybrid charging method is recommended to save energy and keep high efficiency relatively at the same time. However, how to manage the combination percentage of different charging modes in a reasonable way should be dealt with according to the practical requirements.

Key words: electric double layer capacitor (EDLC); energy storage; charge evaluation; numerical calculation; trade-off

Collaborative power supply of new dispersed energy has been attractive recently from a viewpoint of environmental protection and the limited reserves of fossil fuels. However, applying new energy to the dispersed power supply, especially in the case of combinations of various kinds of renewable energies, problems of fluctuation of generated power and/or response characteristics occur, whether stand-alone or grid-connect systems.

For a typical configuration with photovoltaics (PV), the wind power, and the fuel cell (FC), it is obvious that:

- The PV output power fluctuates significantly depending on irradiance and environmental temperature, even shadows sometime;
- The wind power output is unstable depending on weather conditions, perhaps discontinuous;
- The FC output response has a certain time delay depending on its type, mainly because of subsidiary equipments, such as hydrogen or air flow speed control.

In order to solve such problems in an autonomous system, installation of the electric power storage system in this system is necessary, to compensate for the gap between the output from the new energies and the load[1-4]. The electric double layer capacitor (EDLC) is a recent technology based on the well-known electrical phenomenon of an extremely high capacitance/unit area in an electrode-electrolyte interface and a high surface area achievable in activated carbon fibers. Capacitance is available in the range of a few farads to a few hundred farads. It has attracted more and more attention for its prominent advantage in high energy density[5-9]. This paper mainly discusses the charge evaluation of different charging methods.

1 EDLC Review and Basic Charging Circuit

The EDLC is a very complex physical device that is best described by a distributed-parameter model[10-11]. The classical equivalent circuit for EDLC, shown in Fig. 1, is usually adopted because of its simplicity. The three parameters of this circuit are the equivalent series resistance (ESR), the equivalent parallel resistance (EPR), and the capacitance. The ESR is important during charging and discharging since it represents internal heating in the capacitor. It also reduces the terminal voltage during the discharging process due to the resistive divider effect. The EPR only impacts long-term energy storage performance since it models a leakage effect. In general, the capacitor operating time of interest is short enough so that the EPR can be ignored.

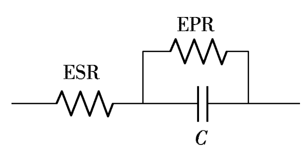

Fig. 1 Classical equivalent circuit for EDLC

Because of low voltage rating, the EDLC must be interconnected to form a capacitor bank for higher voltage applications. For practical application, the installed capacity of the EDLC also deserves more consideration. If the installed capacity is large, although operation becomes easy, it is not so economical. The autonomous operation with small installed capacity is appreciated for renewable energy utilization.

The EDLC discussed in this paper is the Wellgeo M1-001-22-2. 7 type manufactured by Power Systems Co., Ltd. of Japan. The electrochemical principle of this capacitor is based on a limit terminal voltage of about 2. 7 V, and the very product is 59. 4 V with 22 cells connected in a serial string package. And its capacitor is testified to be 55. 34 F with the ESR being 25. 89 mΩ. One typical discharging course of this type is shown in Fig. 2. If supplying a constant load, for example 300 W, it can be sustained for about 270 s, namely 4. 5 min. If supplying a double load, it can be maintained only a bit more than 2 min. As for the reason of the curve, detailed discussions will be provided in later paragraphs.

Received 2009-12-14.

Biography: Xu Qingshan (1979—), male, doctor, associate professor, xuqingshan@seu.edu.cn.

Foundation items: The National Natural Science Foundation of China (No. 50907010), Ph. D. Programs Foundation of Ministry of Education of China (No. 20070286047), Scientific Innovation Foundation for Youngsters of CSEE.

Citation: Xu Qingshan, Bian Haihong, Zhao Weiran. EDLC charging performance for microgrid applications[J]. Journal of Southeast University (English Edition), 2010, 26(3): 415 – 420.

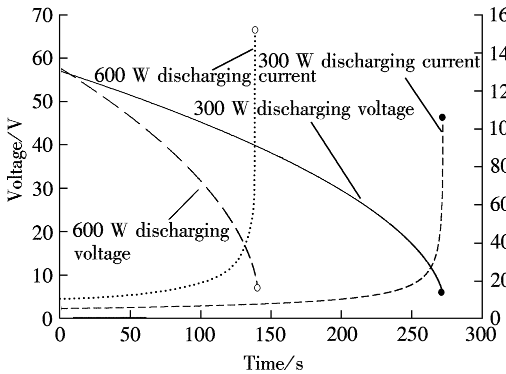

Fig. 2 Typical discharging process of EDLC

In order to maintain a relatively steady voltage, a DC/DC converter is often necessary between the capacitor bank and the DC bus or demand side as the capacitor bank voltage decays while discharging.

In general, an equivalent charging circuit of the EDLC is shown in Fig. 3.

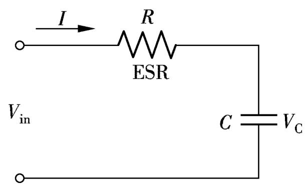

Fig. 3 Equivalent charging circuit of EDLC

The basic topological relationships can be described as

$$V_{in} = V_C + IR \tag{1}$$

$$I = C\frac{dV_C}{dt} \tag{2}$$

$$P_{in} = V_C I + I^2 R \tag{3}$$

where V_{in} is the input charging voltage; V_C is the capacitor voltage; I is the charge current; R is the equivalent series resistance; C is the capacitance of the EDLC; P_{in} is the injection charging power.

2 Numerical Analysis of Different Charging Modes

The converter between the capacitor bank and the demand side also provides possibilities for different control methods of the EDLC charging independently. Traditional charging methods are mainly the constant voltage charging mode (CVCM) and the constant current charging mode (CCCM). For the CVCM, substituting Eq. (2) into Eq. (1), we obtain

$$V_{in} = V_C + RC\frac{dV_C}{dt} \tag{4}$$

The root of this differential equation is commonly expressed as

$$V_C = (V_{C0} - V_{in})\exp\left(-\frac{1}{RC}t\right) + V_{in} \tag{5}$$

where V_{C0} is the initial capacitor voltage. Accordingly,

$$i = C\frac{dV_C}{dt} = \frac{V_{in} - V_{C0}}{R}\exp\left(-\frac{1}{RC}t\right) \tag{6}$$

With the time constant of RC, the capacitor voltage can approach the final voltage approximately after $3RC$ s at least. And the injection power changes every time. For the CCCM, the charging time t_{charge} can be easily calculated by

$$t_{charge} = \frac{C(V_{Cf} - V_{C0})}{I} \tag{7}$$

where V_{Cf} is the final capacitor voltage.

Therefore, the capacitor voltage is

$$V_C = \frac{1}{C}\int I dt = \frac{I}{C}t_{charge} + V_{C0} \tag{8}$$

When $V_{C0} = 0$, the input charging voltage and injection power can be expressed as

$$V_{in} = I\left(R + \frac{t_{charge}}{C}\right) \tag{9}$$

$$P_{in} = I^2\left(R + \frac{t_{charge}}{C}\right) \tag{10}$$

It is obvious that the injection charging power of both the CVCM and the CCCM is changing during the whole charging course. Of course, the EDLC can deal with such conditions. However, for the autonomous microgrid system, how to utilize or store energy to a maximal extent is prominent of all. For example, the PV system often operates with a maximum power peak tracking (MPPT) function, so the power output should be at a definite level if the solar irradiance keeps relatively steady. Therefore, the CVCM or the CCCM seems not so good for such occasions, since the charging power needed is always varying. In such cases, the constant power charging mode (CPCM) is preferred.

For the CPCM, rearranging Eq. (3) yields

$$RI^2 + V_C I - P_{in} = 0 \tag{11}$$

The realistic root of this equation can be found using the quadratic formula.

$$I = \frac{-V_C + \sqrt{V_C^2 + 4RP_{in}}}{2R} \tag{12}$$

There are always a couple of V-I values satisfying Eqs. (1) and (12). For comparing the charging time with the CVCM and the CCCM, further analysis should be carried out. Here a numerical calculation based on the infinitesimal hypothesis approximation is presented; namely, the total charging course is divided into many enough segments which are small enough.

In this way, the equation below is reasonable if the very segment is sufficiently small.

$$I = C\frac{dV_C}{dt} = C\frac{\Delta V_C}{\Delta t} \tag{13}$$

If the range of voltage from V_{C0} to V_{Cf} is divided into N levels, the current at each voltage level can also be calculated from Eq. (12). This set of voltage and current values can then be used to find incremental time steps, the sum of which is the total run time of charging course. The current can be assumed as constant at I_{2n} from V_{2n-1} to V_{2n+1}, and then the time step Δt_n of this voltage transition can be expressed as

$$\Delta t_n = \frac{C(V_{2n+1} - V_{2n-1})}{I_{2n}} \tag{14}$$

When $V_{C0}=0$, let δ represent the step constant,

$$\delta = \frac{V_{Cf}}{N} \tag{15}$$

So the time step Δt_n should be

$$\Delta t_n = \frac{2C\delta}{\left(-2n\delta + \sqrt{(2n\delta)^2 + 4RP_{in}}\right)/(2R)} \tag{16}$$

Let a be one constant,

$$a = \frac{RP_{in}}{\delta^2} \tag{17}$$

Therefore, the ultimate expression of Δt_n is

$$\Delta t_n = \frac{2RC}{\sqrt{n^2 + a} - n} \tag{18}$$

The total charging time is the sum of $N/2$ segment time intervals.

$$t_{charge} = \sum_{n=1}^{N/2} \Delta t_n = (2RC) \sum_{n=1}^{N/2} \frac{1}{\sqrt{n^2+a} - n} \tag{19}$$

If the initial capacitor voltage is not zero, the total charging time can be revised as

$$t_{charge} = \sum_{n=1}^{N/2} \Delta t_n = 2RC \sum_{n=1}^{N/2} \frac{1}{\sqrt{(n+b)^2 + a} - (n+b)} \tag{20}$$

where b is another constant, and $b = V_{C0}/2\delta$.

Perhaps it is not so easy to have a material recognition of the CPCM just from mathematical equations. Tab. 1 presents some intuitionistic data comparisons between the CCCM and the CPCM. Unlike the CCCM, in which the charging power becomes greater with the increase in time, the CPCM charging power keeps constant. If the charging power is larger than the average one of the CCCM, the charging time will be shortened. Energy losses are also provided for comparison. If a shorter time is pursued, there should be more energy loss accordingly.

Tab. 1 Comparison of charging time between CCCM and CPCM

Mode	CCCM ($I=60$ A)	CPCM		
		$P=P_{av}$	$P=60\% P_{max}$	$P=P_{max}$
t_{charge}/s	54. 8	55. 8	48. 2	30. 0
W_{loss}/J	5 106. 3	7 124. 7	8 087. 3	12 167. 0

Note: $P_{av}=1\,877$ W, $P_{max}=3\,657$ W.

Here is a simple PV/EDLC case supposed for the CPCM validation. It is a typical off-grid autonomous system with energy storage. A DC/DC converter is configured with PWM control to proceed with EDLC charging. Fig. 4 only shows the energy storage system, within which the nightly supply circuit is abbreviated. Since the power supplied by PV with MPPT in the specified time region can be deemed as constant, and the main function of the EDLC is to store enough energy from PV, the CPCM is adopted for charging. The main PV parameters are also shown in Tab. 2.

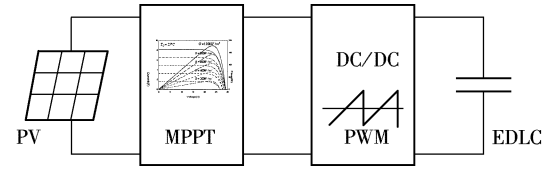

Fig. 4 Simple autonomous storage system of PV/EDLC

Tab. 2 PV parameters of SPG1786T-02E

Parameters	Value
Cell series number	48
STC solar cell temperature/K	298. 15
STC short circuit current/A	8. 15
STC irradiance/(W·m^{-2})	1000
STC open circuit voltage/V	29. 4
Material band gap voltage/V	1. 12
STC current@ MPPT/A	7. 51
STC voltage@ MPPT/V	23. 8

Simulations can be carried out in a Matlab/Simulink environment. The PV array is built up with five modules in series connection and two in parallel connection. The CPCM charging course is simulated under the standard test condition (STC) with charging power being 1 787 W. The curves of the charging current and the EDLC voltage are shown in Fig. 6. The charging current decreases with the increase in the EDLC voltage. The charging time from the simulation results is 58. 452 4 s.

By Eq. (19), suppose that there are 1 000 segments, and the calculated charging time is 58. 550 3 s. The difference between the two results is less than 0. 1 s, which can be regarded in the error scope. For the balance of the charging course, PWM measures should be taken to control the DC/DC voltage transition, which is also shown in Fig. 5.

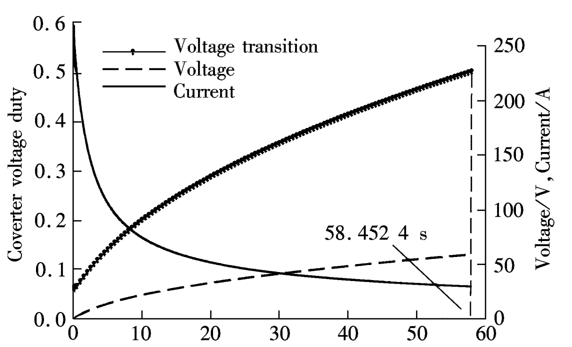

Fig. 5 CPCM simulation results of PV/EDLC

3 Evaluation of Charge Efficiency

For further evaluation of different charging modes, the charging efficiency can be defined for comparison. The efficiency η is related to the energy stored and total injection as

$$\eta = \frac{E_{EDLC}}{E} \tag{21}$$

where E_{EDLC} is the energy stored in EDLC; E is the total charge energy.

CVCM charging efficiency with a constant voltage source V_{cf} can be defined as

$$\eta = \frac{E_{EDLC}}{E} = \frac{\frac{1}{2}C(V_{Cf}^2 - V_{C0}^2)}{\int Vi(t)\,dt} \tag{22}$$

Inserting Eq. (6), namely,

$$\eta = \frac{\frac{1}{2}C(V_{Cf}^2 - V_{C0}^2)}{V\int \frac{V_{Cf} - V_{C0}}{R}\exp\left(-\frac{1}{RC}t\right)dt} = \frac{1}{2}\frac{V_{Cf} + V_{C0}}{V_{Cf}} \tag{23}$$

When the initial voltage $V_{C0} = 0$, the efficiency is only 50% and is independent of the series resistance R. As for renewable energy utilization, charging and discharging are frequent, and a charging course with low voltage initially occurs mostly under general conditions, which results in a bit improper towards the CVCM.

If the EDLC is charged by a constant current source I, the efficiency is obtained as follows:

$$\eta = \frac{E_{EDLC}}{E} = \frac{\frac{1}{2}C(V_{Cf}^2 - V_{C0}^2)}{\int (V_C(t) + IR)\,I\,dt} \tag{24}$$

By Eq. (8), Eq. (24) can be substituted into

$$\eta = \frac{\frac{1}{2}C\left[\left(V_{C0} + \frac{I}{C}t_{charge}\right)^2 - V_{C0}^2\right]}{Rt_{charge}I^2 + I\int_0^{t_{charge}}\left(V_{C0} + \frac{I}{C}t_{charge}\right)dt} = \frac{V_{C0} + \frac{It_{charge}}{2C}}{IR + \left(V_{C0} + \frac{It_{charge}}{2C}\right)} \tag{25}$$

Inserting Eq. (7), Eq. (25) can be rearranged as

$$\eta = \frac{\frac{1}{2}(V_{Cf} + V_{C0})}{IR + \frac{1}{2}(V_{Cf} + V_{C0})} \tag{26}$$

It is obvious that the efficiency of the CCCM is greater than 90.9% when $(V_{Cf} + V_{C0})/2 > 10IR$, namely $I < (V_{Cf} + V_{C0})/(20R)$, which can be easily satisfied in general. Fig. 6 illustrates the sketch of efficiency against different initial capacitor voltages and charging currents. The CCCM with a low current and high initial voltage point is more efficient. Of course, this is purely from the viewpoint of efficiency, and low charging current results in longer charging time apparently.

As for the CPCM, the efficiency is

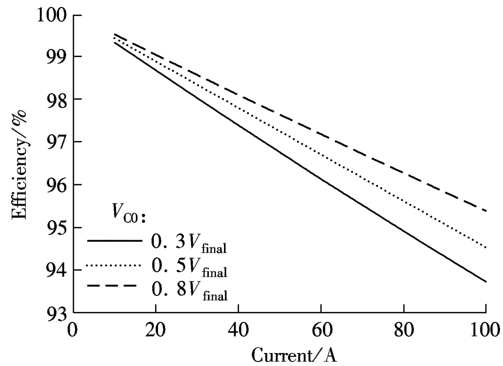

Fig. 6 Sketch of CCCM efficiency

$$\eta = \frac{E_{EDLC}}{E} = \frac{\frac{1}{2}C(V_{Cf}^2 - V_{C0}^2)}{P_{in}t_{charge}} \tag{27}$$

The efficiency of the CPCM is related to the product of charging power and charging time. Generally speaking, the efficiency decreases with the increase in charging power though the charging time becomes shorter at the same time. Fig. 7 presents the distribution of energy amount of loss and EDLC stored in every 10% charging stage. It is evident that the energy loss of the CPCM is mainly centralized at the very beginning of the charging course, when the EDLC voltage is relatively low while the charging current is relatively great which results in greater energy consumed in the ESR. Therefore, the CPCM would be much better in the case of avoiding the initial charging course when the capacitor voltage is relatively low.

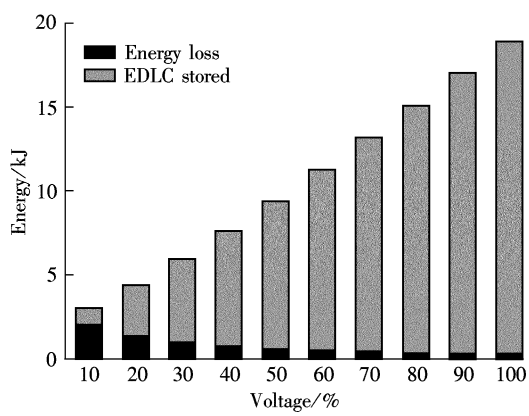

Fig. 7 Distribution of charging energy amount

4 Optimization of Charging Trade-Off

In fact, the capacitor voltage can also be expressed as the division of electric quality and capacitance. The electric quality accumulated in the capacitor can be reckoned by the integral of electric current through the capacitor. Since the capacitance is constant, the EDLC voltage can be demonstrated with the down surrounding area of the current curve to some extent. As long as the initial and final conditions are the same, equal areas should be satisfied for different charging modes.

For the CCCM and the CPCM, two conditions are shown in Fig. 8 due to different charging powers. Only when the charging power is less than the power exhausted in the ESR of the CCCM, the charging curve of the CPCM comes into being as in Fig. 8(b), otherwise, the curve in Fig. 8(a) represents the most instances. For both conditions, the area of *ABEO* which represents the CPCM is equal to the one of *CDFO* which represents the CCCM. It is obvious that the CPCM charging time is less than that of the CCCM except when the charging power is very small as in Fig. 8(b). From the viewpoint of the shortest charging time, the *AMD* curve can be referred to, namely, the CPCM first, then the CCCM. However, the final point is not *D*, even in the advance of point *B*. The crucial shortcoming of this method lies in that more energy is wasted for the relatively big current during the whole charging course. The energy-saving mode can be referred to the *CMB* curve, which really avoids a greater energy loss of the CPCM at the very beginning, but the final point is even much later than point *D*. This hybrid charging method with the CCCM and the CPCM should be preferred for the autonomous renewable systems.

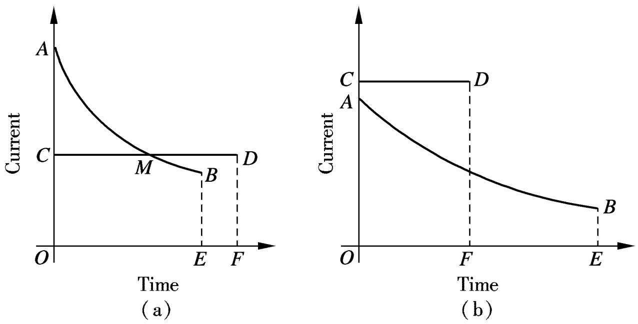

Fig. 8 General sketch of CCCM and CPCM. (a) CCCM; (b) CPCM

However, the mode-shifting point is a problem. An early shift causes a smaller injection power for the CPCM which leads to longer charging time. A later shift will bring greater energy loss in spite of shorter time. Fig. 9 and Fig. 10 illustrate the charging curves of voltage and current with shifting at 40% and 80% of final voltage, respectively. For more clear understanding, Tab. 3 is presented for different operating scenarios with various mode-shifting points of the CCCM and the CPCM. Charging time, energy loss and efficiency are all reviewed.

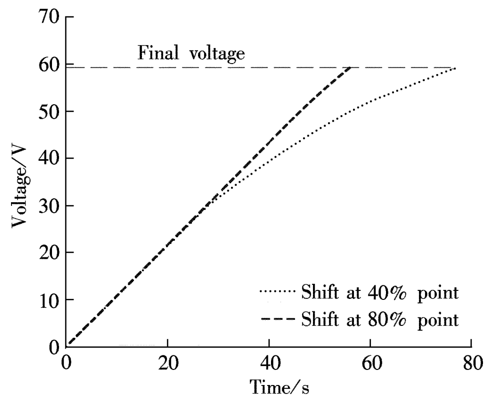

Fig. 9 Charging curve of EDLC voltage

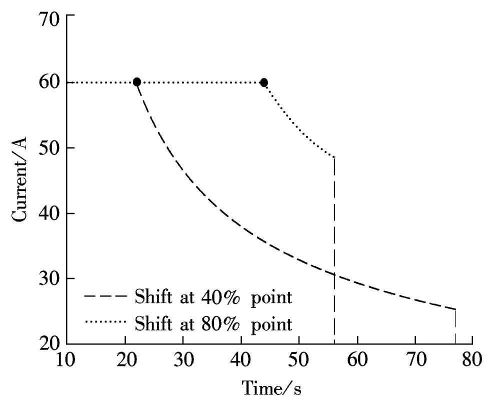

Fig. 10 Charging curve of EDLC current

Tab. 3 Comparisons with different mode-shifting points of CCCM and CPCM

$\frac{V_{shift}}{V_{final}}$ /%	T/s			W_{loss}/J			η/%		
	CCCM	CPCM	Total	CCCM	CPCM	Total	CCCM	CPCM	Total
10	5.478 7	218.091 6	223.570 3	510.6	1 401.4	1 912.1	65.660 0	98.570 0	98.080 0
20	10.957 3	118.499 9	129.457 2	1 021.3	1 786.8	2 808.1	79.269 8	98.129 2	97.204 1
30	16.436 0	78.099 2	94.535 2	1 531.9	1 939.8	3 417.3	85.154 0	97.863 3	96.566 2
40	21.914 6	55.269 7	77.184 3	2 042.5	1 934.9	3 977.4	88.436 3	97.695 1	96.085 5
50	27.393 3	40.013 0	67.406 3	2 553.2	1 810.3	4 363.5	90.530 0	97.587 3	95.721 8
60	32.872 0	28.711 4	61.583 3	3 063.8	1 589.4	4 653.2	91.981 8	97.519 4	95.450 7
70	38.350 6	19.736 8	58.087 5	3 574.4	1 287.9	4 862.3	93.047 6	97.478 7	95.255 9
80	43.829 3	12.248 2	56.077 5	4 085.1	917.0	5 002.1	93.863 3	97.457 2	95.126 2
90	49.307 9	5.766 8	55.074 8	4 595.7	485.5	5 081.2	94.507 7	97.449 3	95.052 9
100	54.786 6	0	54.786 6	5 106.3	0	5 106.3	95.029 7	0	95.029 7

Apparently, with the shifting point later, the charging time is shortened, while the energy loss increases at the same time. In fact, the efficiency of the CCCM segment increases but the total efficiency declines. This is a typical trade-off between time and energy loss. Since the shorter time and less energy loss are anticipated, a trade-off index λ can be defined as

$$\lambda = \frac{\Delta T}{\Delta W_{loss}} \tag{28}$$

where $\Delta T = (T_{former} - T_{now})/T_{now}$, which delegates for the decreased time percentage now, and $\Delta W_{loss} = (W_{now} - W_{former})/W_{former}$, with the meaning of increased energy loss percentage compared with the former.

Fig. 11 shows the curve of trade-off index changes against different mode-shifting options, which can be regarded as the effective cost of energy loss for a shorter time. As the curve is presented, it may be better to bring the mode-shifting into effect around the thirty or fifty percentage level of final voltage. Of course, this is just the suggestion taking the effective cost into account. In some cases, perhaps the charging time is not a problem, while in other cases the energy loss is not so important, which maybe creates different analysis options.

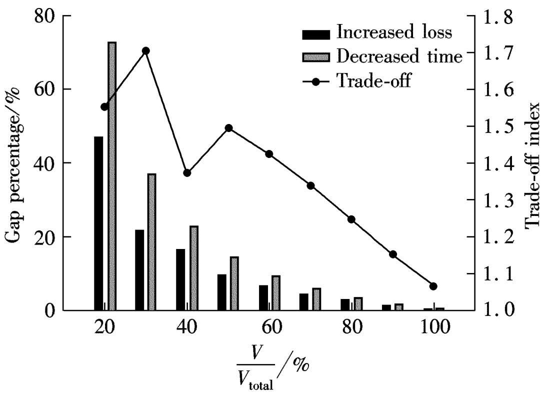

Fig. 11 Curve of trade-off index changes against different mode-shifting options

5 Conclusion

The EDLC is now playing a greater role in renewable hybrid systems due to its characteristic merits. Different charging modes are mainly discussed in this paper. Hybrid charging modes with the CCCM and the CPCM are recommended to adopt for saving energy and keeping high efficiency at the same time. Numerical calculation of the CPCM is also presented and proved to be reasonable and applicable for practical charging analysis.

A trade-off index for hybrid charging is proposed in this paper for autonomous energy storage systems. In fact, the CVCM is often applied at the very end of the charging course, which can restrain the charging current for lower energy loss exhausted in the ESR to some extent and also hold high efficiency at the same time. How to utilize and manage the relationship of different charging modes in a reasonable way can be dealt with according to practical needs.

References

[1] Mutoh N, Inoue T. A controlling method for charging photovoltaic generation power obtained by a MPPT control method to series connected ultra-electric double layer capacitors [C]// *Proceedings of the 39th Annual Meeting of IEEE Industry Application Society*. Seattle, WA, USA, 2004: 2264 − 2271.

[2] Mishima T, Ohnishi T. Experimental evaluation of the EDLC based power compensator for a partially shaded PV array [C]// *Proceedings of the IEEE IECON*. Roanoke, VA, 2003: 1308 − 1313.

[3] Seita K, Takano I, Nishikawa H, et al. A study of operation characteristics of UPFC type dispersed power supply system with FC, PV and EDLC by improved EMAP model [C]// *Proceedings of the IEEE Power System Conference and Exposition*. New York, USA, 2004: 289 − 294.

[4] Kinjo T, Senjyu T, Urasaki N, et al. Output leveling of renewable energy by electric double-layer capacitor applied for energy storage system [J]. *IEEE Transactions on Energy Conversion*, 2006, **21**(1): 221 − 227.

[5] Zubieta L, Bonert R. Characterization of double-layer capacitors for power electronics applications [J]. *IEEE Transactions on Industry Application*, 2000, **36**(1): 199 − 205.

[6] Spyker R L, Nelms R M. Analysis of double-layer capacitors supplying constant power loads [J]. *IEEE Transactions on Aerospace and Electronic Systems*, 2000, **36**(4): 1439 − 1443.

[7] Mutoh N, Inoue T. A control method to charge series-connected ultraelectric double-layer capacitors suitable for photovoltaic generation systems combining MPPT control method [J]. *IEEE Transactions on Industrial Electronics*, 2007, **54**(1): 374 − 383.

[8] Sugimoto S, Ogawa S, Katsukawa H, et al. Study on series-parallel changeover circuit of capacitor bank for energy storage system utilizing electric double-layer capacitors [J]. *Transactions of IEEJ*, 2002, **122-B**(5): 607 − 615. (in Japanese)

[9] Gao Lijun, Dougal R A, Liu Shengyi. Power enhancement of an actively controlled battery/ultracapacitor hybrid [J]. *IEEE Transactions on Power Electronics*, 2005, **20**(1): 236 − 243.

[10] Spyker R L, Nelms R M. Classical equivalent circuit parameters for a double-layer capacitor [J]. *IEEE Transactions on Aerospace and Electronic Systems*, 2000, **36**(3): 829 − 836.

[11] Bohlen O, Kowal J, Sauer D U. Ageing behavior of electrochemical double layer capacitors [J]. *Journal of Power Sources*, 2007, **172**(1): 468 − 475.

微网系统中超级电容充电性能研究

徐青山　卞海红　赵伟然

(东南大学伺服控制技术教育部工程研究中心,南京 210096)

摘要:为了考察超级电容微网储能性能,以典型超级电容实际产品为对象,针对恒电压、恒电流以及恒功率3种充电模式,研究充电时间及储能效率问题.提出了各种充电模式的数值计算方法,并利用严格的数学推导讨论了不同充电模式的效率问题.同时通过一个独立PV/EDLC系统验证了计算的准确性.最后研究分析了不同充电模式的充电速度与能量损失的权衡问题.研究结果表明:与传统的恒电压和恒电流充电方式相比,恒定功率充电方式更适用于微网系统.混合充电方式在实际应用中会更高效节能,但需根据实际具体要求合理处理不同充电模式的组合比例.

关键词:超级电容;能量存储;充电评估;数值计算;权衡

中图分类号:TM53