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A control strategy for optimizing the power flows supplied by two different storage units

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***Abstract*—The DC distribution networks can easily benefit from integration of electrical storage systems, such as batteries and supercapacitors, to manage the network operations. A proper combination of these two storage units can lead to a storage system able to satisfy power requests lasting from seconds to hours. However, the use of more than one storage unit gives rise to the problem of deciding how to split the power between the two technologies. In the paper, authors propose a control strategy to divide the power demand between the two storage units ensuring, at the same time: i) a peak shaving action for the interface converter opportunely slowed; ii) the lifetime increase of storage units by means of a proper control adapted to the dynamic performances of each storage device; iii) the keeping of the state of charge of each unit around a desired value. In the paper, the effectiveness of the proposed strategy is shown by means of numerical simulations. In particular, very good results are obtained also when the power demand is completely random.**

***Index Terms*-- AC-DC power conversion, DC power systems, electrical storage systems, peak shaving**

I. Introduction

The growing diffusion of renewable energy sources is changing the topologies of power distribution networks. In particular, all the problems concerning voltage regulation and power quality have to take into account the possibility that generation units are present at distribution network level. In this scenario DC distribution grids are becoming more and more interesting because they can achieve both the goals of improving the distribution efficiency and of ensuring high power quality to the loads. The diffusion of renewable energy sources highlights the necessity of storing energy when it is available from the main source and it is not required by the loads. Furthermore, almost all storage systems, at present available, can be easily connected to DC networks. So, the possibility to build some DC networks interconnected to AC distribution networks to feed some loads is becoming very actual and convenient.

The interfacing between the AC and the DC network is, usually, realized by means of a 4-quadrant Voltage Source Inverter (VSI). Acting on this converter it is possible to guarantee a high power quality on the DC network. However, if a strongly variable load is present on the DC side, in order to keep the DC power quality at high level, a fast control of the VSI is necessary. This control can cause a reduction of power quality level on the AC network giving rise to voltage fluctuations and current harmonics [3]. If a storage system is connected on the DC network, this can be used to supply to the load the alternate component of the power, so shaving the power supplied by the AC network and, consequently, improving its power quality.

The amount of energy and the dynamic capabilities necessary to carry out this goal depend on the peculiarities of the loads (mainly on the speed variation and on the ratio between maximum and mean power). The characteristics of the different storage technologies are different. In particular, two very important parameters in the choice of the optimal technology are the energy density and the power density. Usually, indeed, high energy density corresponds to low power density and vice versa. For this reason, the Ragone diagram is often used to choose the storage device starting from the specific requests of the loads. In Fig. 1 a Ragone plot is reported [4].

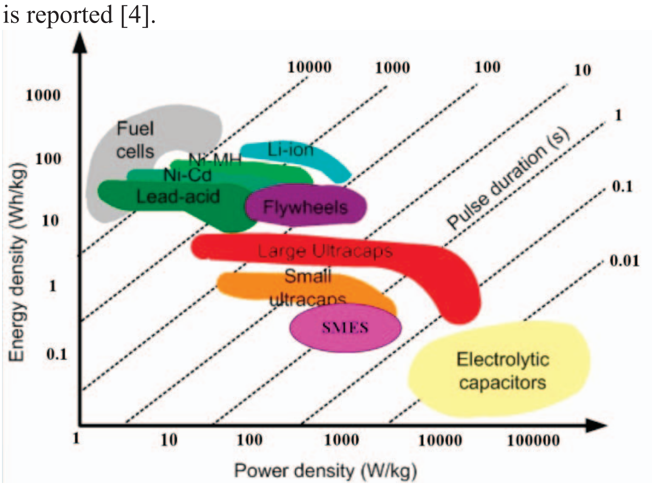

Fig. 1: Ragone plot of different storage technologies.

The choice of the most suitable technology and size of the storage system should change case by case and should be updated at each connection of new loads on the network. However, the use of only one technology leads to oversize the energy device. Indeed, high energy density devices are oversized to cover the power request, while high power density devices are oversized to store the desired amount of energy.

A possible solution to this problem is the use of more than one

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technology in order to achieve a flexible storage unit. In particular, in this paper the possibility of using a storage system constituted by supercapacitors and electrochemical batteries is analysed. The different characteristics of the two technologies can bring to a storage unit characterised by high power density and high energy density. At the same time the cost can be limited because the use of batteries covering slow dynamic requests increases, significantly, their life [5]. In the paper a control strategy is proposed. The aim is threefold: i) to control the VSI and the storage devices in order to obtain a peak shaving action on the power requested from the grid; ii) the controllers of the storage units are tuned to bound their dynamic behaviour within properly set constraints thus making them work in optimal conditions so to extend their lifetime; iii) to ensure the automatic recharge of the storage units without information about the loads in order to keep the whole system ready to cope with unpredictable power requests. The effectiveness of the proposed strategy is shown by means of numerical simulations.

II. DC SYSTEM TOPOLOGY AND MODELING

The DC system under consideration is constituted by a VSI, two storage units equipped with supercapacitors and electrochemical batteries, interfaced to the DC bus by power converters, and a variable load. In Fig. 2 a schematic representation of the network is depicted.

The storage system is constituted by supercapacitors and electrochemical batteries because their characteristics are complementary. In particular, supercapacitors present high power density while electrochemical batteries have high energy density. For this reason the former can be used to supply power variations occurring in some seconds while the latter are suitable to supply loads for minutes or hours [6]-[7]. In this paper authors refer to a storage unit sized to shave the power request coming from the load. No stand-alone operations have to be ensured so the battery pack is very small and traditional batteries can be used without an unaffordable increasing of the plant costs. However, the proposed control strategy is able to make the system operate in stand-alone conditions if the storage systems has been correctly sized to supply the full load power for the necessary time.

The modeling of the two units has been realized with very simple models because their dynamic intervention is controlled by the converters. So, each unit works always in dynamic conditions that it can afford. In particular a series RC model has been used for supercapacitors, while a voltage generator linearly dependent on the state of charge with a series resistance has been used to model the batteries [8]-[9]. Thus battery voltage V results:

$$V = V_0 + V_1 Q - R I \tag{1}$$

where Q is the state of charge in p.u., I is the supplied current and V_0 and V_1 are constants.

In order to control the power supplied and absorbed by each of the storage units a 2-quadrant DC/DC converter is used to interconnect them to the DC bus.

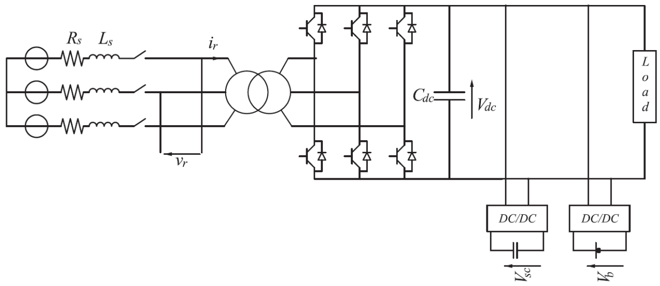

Fig. 2. Scheme of the DC network

The VSI interfacing the AC and the DC grid is used to regulate the power exchanged between the two networks. In particular, a PLL (Phase Locking Loop) algorithm is implemented to lock the phase of the AC voltage and a decoupled control on active and reactive power is implemented [10]. In particular the reactive power is controlled to zero while the active power is controlled following the references obtained by the control strategy presented in the next section.

III. THE CONTROL STRATEGY

All the three converters of the network are controlled with two feedback chains; the internal chain controls the current supplied by the converter while the external chain controls the output voltage.

The main goals of the control strategy are:

1. to shave the power supplied by the AC network;
2. to keep the state of charge of each storage unit near the desired value;
3. to realize a fully plug and play storage system.

In order to shave the power required by the AC network it is necessary to make the storage units able to supply the power quicker than the interface converter. This can be achieved acting on the bandwidths of the controllers of the three units. In defining the bandwidths of the controllers the dynamics of the different storage devices is taken into account. In this way each storage unit works in its optimal dynamic condition. In particular, the fastest control will be applied to supercapacitors while the slowest to the VSI. In tuning the regulators, it is necessary to separate the dynamics of the three converters in order to avoid oscillations in the power exchanged between the systems. To make the VSI blind to load oscillations a very low bandwidth in the PI regulator of the interface converter is used. However, in order to speed up the answer a feed forward action is introduced. This feed-forward action is realized adding to the output of the PI regulator, the mean power supplied to the load in a significant window of the recent past.

In order to keep the desired medium state of charge of the storage units it is necessary to give a feedback to the control about the actual state of charge. In particular, each storage unit will try to set on the DC bus a voltage that is function of the own state of charge:

$$V_{dc,ref} = V_{dc}^{*} - k\left(Q_{storage,ref} - Q_{storage,meas}\right) \tag{2}$$

where with the index *ref* and *meas* the reference and the measured values are respectively indicated. Moreover, V_{dc}^* indicates the DC voltage reference of the interface converter and with Q it is made reference to the state of charge. At steady state, if the state of charge of one storage unit is lower than the desired value the DC voltage reference of this storage unit is reduced and, consequently, an amount of power is drawn from the DC bus to recharge the unit. In this way, the control system automatically keeps the state of charge of the storage unit around the desired value. Moreover, from (2) it is clear that the reference voltage for each storage unit is obtained only using the DC bus voltage and the state of charge. No external information or coordination between the units is needed. This feature makes it possible to add and substitute the storage units without modifying the system. A fully plug and play structure is, therefore, obtained. This structure can be easily updated if the network characteristic changes for the introduction of new loads or generation units. In Fig. 3 a scheme of the control chain for each one of the storage system is reported.

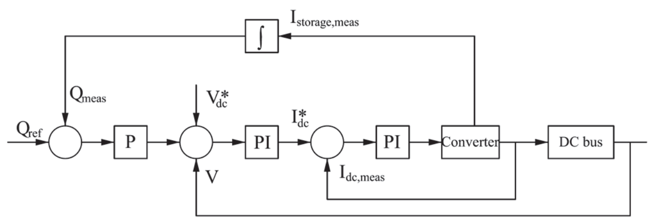

Fig. 3. Control scheme of each storage device

The tuning of the regulators is realized as follows:

- the current PI regulator is tuned with the high possible bandwidth compatible with the switching frequency, i.e. one decade lower than the switching frequency;
- the voltage PI regulator is tuned with a bandwidth such that the device operate with the desired dynamic. In particular, the two controllers are tuned with bandwidths far at least of one decade to avoid power oscillations between them;
- the state of charge proportional regulator is tuned to the ratio between the maximum allowed state of charge variation and the maximum desired dc voltage variation.

The VSI controller is tuned with a very slow bandwidth, i.e. a decade lower than the slower storage unit.

In order to highlights the good acting of the storage devices, in the following the system reported in Fig. 2 is simulated with and without the presence of the two storage units. When no storage system is connected the VSI has to cover all the power request of the loads. So, a slow controller can lead to a very oscillating DC voltage with consequent very low power quality on the DC side. On the contrary a fast VSI controller can achieve a good quality of DC voltage but it needs a full power sized inverter and can cause oscillations on the AC voltage. In particular, flicker effect can appear if the power oscillating demand is at low frequencies (i.e. some Hz).

In the following, three systems are simulated:

1. the system equipped with the two storage units;
2. the VSI working alone with the same dynamic as set at point 1;
3. the VSI working alone with a faster dynamic control.

IV. Simulation Results

In order to show the capability of the control strategy of achieving the goals given in Section III, for each system configuration three simulations have been carried out. The power required by the load, in kW @400 V, is given by the following expressions:

1. $P_L(t) = 10 + 10\sin(2\pi\, 0.5t) + 10\sin(2\pi\, 5t)$;
2. $P_L(t) = 10 + 5\ F_r(2\pi\, 0.5t) + 2\ F_r(2\pi\, 5t)$.
3. $P_L(t) = 10 + 10\ F_r(2\pi\, 0.5t) + 10\ F_r(2\pi\, 5t)$.

where $F_r(x\ t)$ is a random function changing value every $2\pi/x$ seconds.

For all the simulations at time t=30s the power required is doubled. The parameters of the simulated system are reported in Table I while the parameters of the storage units are reported in Table II.

TABLE I- MAIN DATA OF THE SIMULATED SYSTEM

AC Rated Voltage [V]	Line resistance [mΩ/km]	Line inductance [mH/km]	Line length [m]	DC rated voltage [V]	DC bus capacitance C_{dc} [mF]
400	290	1.2	100	400	5.8

TABLE II- MAIN DATA OF THE SIMULATED STORAGE UNITS

Supercapacitor		Battery			
R [mΩ]	C [F]	R [mΩ]	V_0 [V]	V_1 [V]	Capacitance [Ah]
10	1	100	170	100	1

The aim of the paper is to find and test an optimal control strategy of an already sized system. For this reason the optimal sizing of the storage units has not been performed and the values in Table II have been chosen to simulate a realistic system.

In the first simulation the load is composed by three components: a mean power of 10 kW, a first sinusoidal component at 0.5 Hz and amplitude of 10 kW and a second sinusoidal component at 5 Hz and amplitude of 10 kW. In Fig. 4 the mean required power and the power supplied by the converter interface are reported. In Fig. 5 the oscillating component of the power demand and the power supplied by supercapacitors and batteries are reported. From Figs. 4 and 5 it is clear that the maximum power supplied by the VSI, 23.2 kW, is lower than the maximum required power, 60 kW. Moreover, it is evident that the supercapacitors supply only the oscillating component of the power demand while the batteries cover the power during the transients necessary to the interface converter to reach the mean power demand.

The second simulation has been carried out to show the capability of the control strategy of answering also to unpredictable power request. For this reason the load power is constituted by a mean power of 10 kW, a random oscillating power of amplitude of 5 kW and changing every 2 s and another random oscillating power of amplitude 2 kW and changing every 200 ms. In Fig. 6 and 7 the power supplied by the interface converter and by the storage units are reported, respectively.

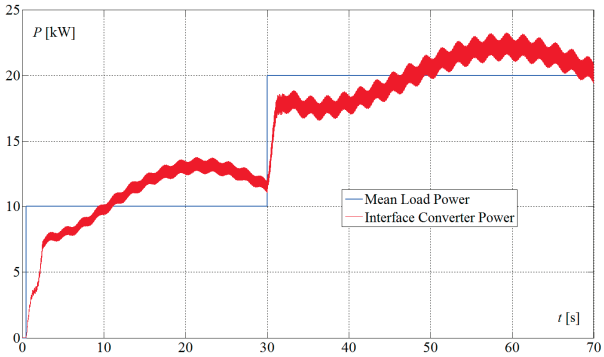

Fig. 4. Case 1 – Power supplied by the inverter interface

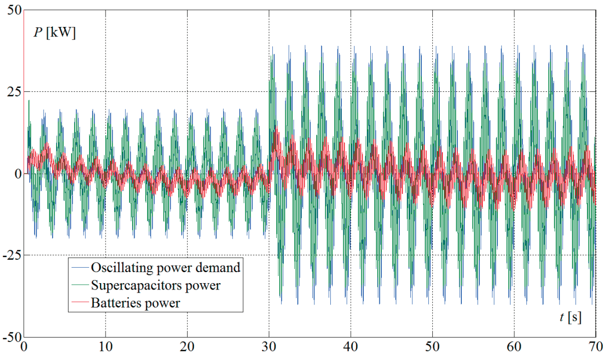

Fig. 5. Case 1 – Power supplied by supercapacitors and batteries

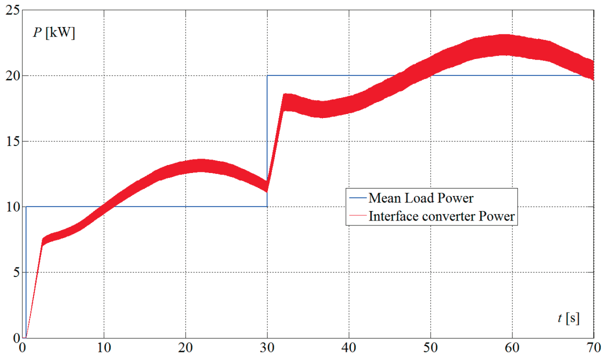

Fig. 6. Case 2 – Power supplied by the inverter interface

From Figs. 6 and 7 it is evident that the system works in a very similar way also with random power requests.

In the third simulation the load is composed by three components: a mean power of 10 kW, a first random component of 10 kW changing every 2 s and a second random component of 10 kW changing every 200 ms.

The second and the third simulations are carried out with a high harmonic content load. Indeed, contrarily to the first case the harmonic content results higher and distributed at any frequencies, due to the random function. This is clear from the observation of Figs. 6-9. In Figs. 8 and 9 the power supplied by the interface converter and by the storage units are reported, respectively.

The dynamic of the VSI changes, but the maximum required power is however limited to 26 kW. Supercapacitors cover the majority of the oscillating power request. In any case the spectra of the load power is distributed at high frequencies for all devices. This is why this spectra is much higher than the bandwidth of all the converters. In any case, the higher contribution is given by the faster converter, while the lower contribution is given by the slower device.

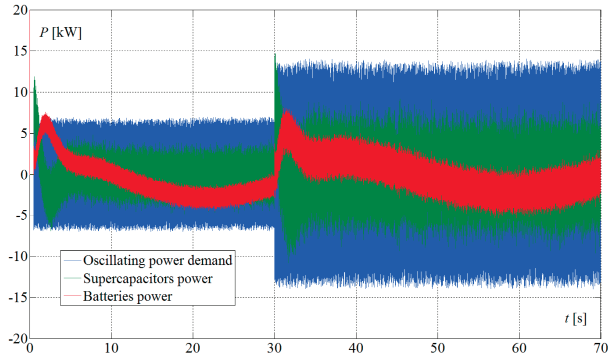

Fig. 7. Case 2 – Power supplied by supercapacitors and batteries

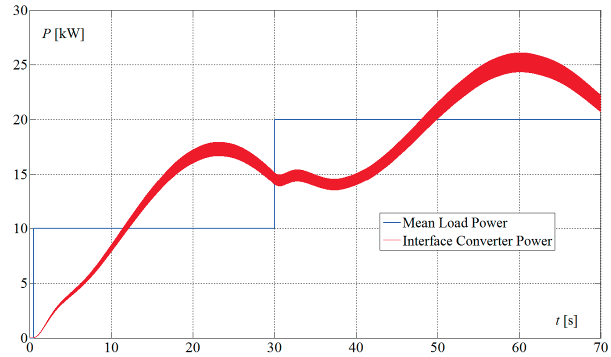

Fig. 8. Case 3 – Power supplied by the inverter interface

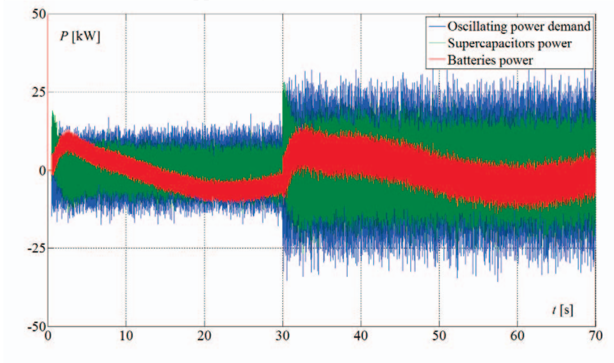

Fig. 9. Case 3 – Power supplied by supercapacitors and batteries

As above discussed the proposed control strategy is able to ensure the charge of the storage devices by means of (2). In Figs. 10 and 11 the state of charge of supercapacitors and batteries in the three cases simulated are reported. Indeed, for supercapacitors the voltage has been plotted since, for a linear capacitance, it directly represents the state of charge.

The state of charge keeps around the desired value (i.e. 250V for supercapacitors and 0.8 p.u. for the battery state of charge). The oscillation is essentially due to the alternate component of the power demand and results higher when the power demand oscillates slowly. Indeed, the high frequency power oscillation practically does not affect the state of charge of the two devices. This is due to the low-pass effect of the state of charge dynamic behavior.

As above discussed the presence of the storage system allows a good power quality level both on DC and AC networks. On the contrary the use of only the VSI implies a lower power quality level at least on one side. In order to point out the effectiveness and the importance of the storage system proposed the DC and AC voltage have been investigated. A useful parameter to evaluate the quality level of the AC network is the estimation of the flicker effect. In order to evaluate it, according with [11]-[12] a flickermeter has been set up. The Perception of flicker short term (PST) value has been evaluated for all the simulated cases and its values are reported in Table III. It is worth noting that, as reported in the technical normative [11]-[12], the value 1 for the PST is the limit of the flicker appreciable by human sight. Unfortunately the flicker has not yet defined for DC network. So, the diagrams of the DC network and the percent variations are used to evidence the difference between the answer of the three system configurations discussed in Section III. the In Figs. 12-14 the DC bus voltage in the three simulations are reported.

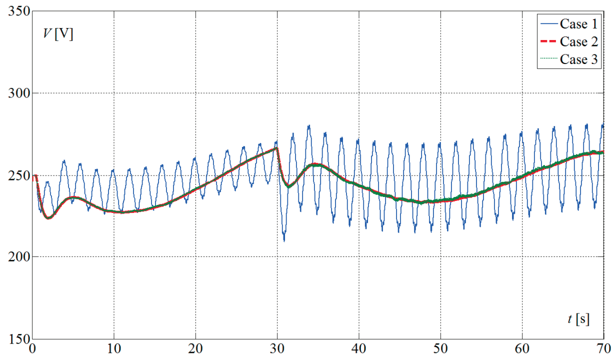

Fig. 10. Supercapacitor voltage during the three simulations

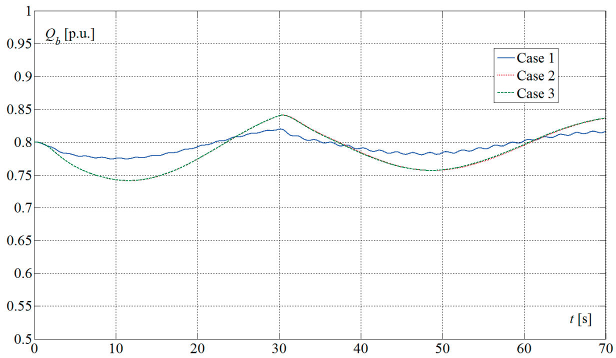

Fig. 11. Battery state of charge during the three simulations

For the DC voltage the most critical case is the case 1. This is because the low frequency spectrum of the first case (the oscillations are concentrated at 0.5 and 5 Hz) are not filtered at all by the DC bus capacitance. It is clear that it is not possible to operate with the VSI inverter tuned as slow as when the storage devices are present. Indeed, the DC voltage oscillations are unacceptable at steady state in the first case and during transients in the second and third case. The fast control on the VSI gives rise to acceptable DC voltage levels also if it is not so good as with the storage devices. However, the fast control on the VSI, as expected, causes problems on the AC side. In Table III the PST values for the three configurations in the three simulations are reported.

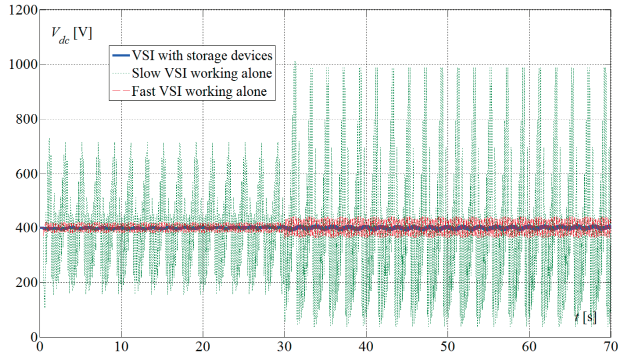

Fig. 12. Case 1: DC bus voltage

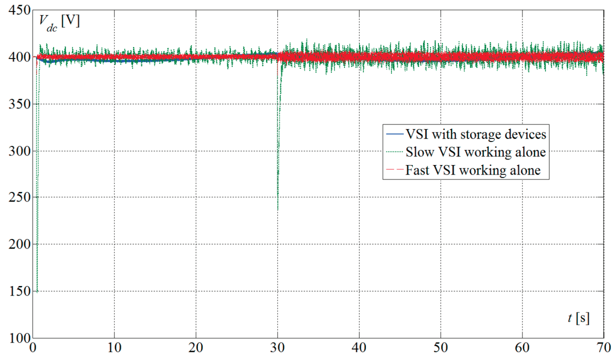

Fig. 13. Case 2: DC bus voltage

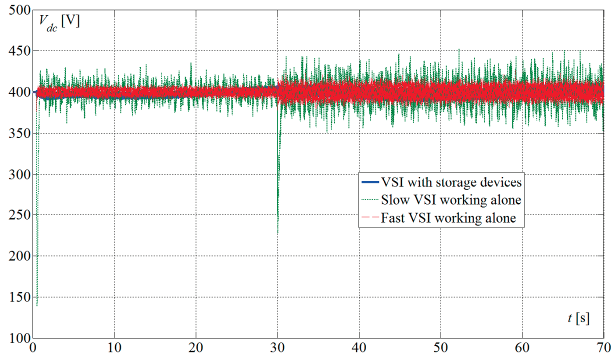

Fig. 14. Case 3: DC bus voltage

The PST is evaluated in the two steady state conditions: for $10s < t < 20s$ and for $50s < t < 60s$. In the same table information about the DC voltage variations are reported. In particular, the maximum DC voltage variations are evaluated in the two steady state conditions and the transient voltage drop occurring at $t = 30s$ (i.e. at the load change) is also reported.

From Table III clearly results that it is not possible to obtain good results for both AC and DC side using only the VSI. On the contrary the use of the two storage devices with the proposed control strategy allows the absence of flicker on the AC side and, at the same time, the voltage variation always lower than ±2.5%.

TABLE III - COMPARISON BETWEEN THE SYSTEM WITH AND WITHOUT THE STORAGE DEVICES

		Flicker PST		$\Delta V_{dc}/V_{dc}$ [%]		$\Delta V_{dc}/V_{dc}$ [%]
		10s<t <20s	**50s<t <60s**	**10s<t <20s**	**50s<t <60s**	**Transient**
With storage	Case 1	0.4163	0.4144	2.45	4.45	2.11
	Case 2	0.4693	0.4316	1.31	2.01	2.61
	Case 3	0.4689	0.4304	2.38	4.41	2.83
Only slow VSI	Case 1	0.5259	0.7456	**139**	**237**	**98.6**
	Case 2	0.4074	0.4123	6.36	8.17	**40.8**
	Case 3	0.4076	0.4121	16.1	24.2	**43.3**
Only fast VSI	Case 1	**1.8929**	**3.7142**	9.82	19.4	15.0
	Case 2	0.4118	0.4344	2.03	4.12	6.01
	Case 3	0.4602	0.5657	5.80	11.8	9.9

V. CONCLUSIONS

The large diffusion of intrinsically DC loads on the distribution networks gave rise to an increased interest in DC distribution networks. Moreover, these are attractive also because they make easy the integration of both distributed generation units and storage systems. In the paper a DC distribution network interconnected with a traditional AC distribution network has been studied. In particular, it has been shown that, introducing an adequate storage system on the DC bus, it is possible to realize a peak shaving action and, at the same time, it is possible to ensure a high level of power quality on both the AC and DC network. It is convenient to build the storage system by using more than one technology to obtain an integrated system presenting high power and high energy density and limited costs avoiding the use of innovative electrochemical storage devices. In the paper a hybrid system constituted by supercapacitors and electrochemical batteries has been proposed.

In order to achieve the mentioned goals of power regulation and shaving a proper control strategy has been proposed. By means of numerical simulations it has been shown the effectiveness of the control algorithm proposed also when the power demand is randomly variable. A future development will comprise a set of experimental tests to check the effectiveness of the proposed control strategy.

VI. REFERENCES

[1] M. Brenna, E. Tironi, G. Ubezio, T. Kaipia, J. Lassila, P. Salonen, J. Partanen, “Distributed generation in DC distribution system”, CIRED Conference, Wien 21-24 May 2007, Paper No. 0385.

[2] T. Kaipia, J. Lassila, P. Salonen, J. Partanen, 2007, “Application of low voltage DC-distribution system - a techno-economical study”, Proceedings CIRED Conference, Wien 21-24 May 2007.

[3] V. Musolino, L. Piegari, E. Tironi, L. Martini, C. Tornelli, A. Brambilla: “Simulations and field test results for potential applications of LV DC distribution network to reduce flicker effect”, *Harmonics and quality of power 21st IEEE International Conference on,* September 2010

[4] S.R. Holm, H. Polinder, J.A. Ferreira, P. van Gelder and R. Dill, “A Comparison of Energy Storage Technologies as Energy Buffer in Renewable Energy Sources with respect to Power Capability”, Young Researchers Symposium, Leuven, February, 2002

[5] Yan Jia; Shibata, R.; Yamamura, N.; Ishida, M.; , "A Control Method of Prolonging the Service Life of Battery in Stand-alone Renewable Energy System using Electric Double Layer Capacitor (EDLC)," *International Conference on Power Electronics and Drives Systems, 2005. PEDS 2005.*, vol.1, pp.228-233

[6] E. Tironi, V. Musolino: “Supercapacitor characterization in power electronic applications: proposal of a new model”, International Conference on Clean Electrical Power, 2009, pp. 376 – 382

[7] Leuchter, J.; Bauer, P.; Stekly, V.; , "Battery-supercapacitors mixed as electrical power buffers," *Power Electronics, Machines and Drives (PEMD 2010), 5th IET International Conference on* , 19-21 April 2010

[8] Ceraolo, M.; , "New dynamical models of lead-acid batteries," *IEEE Transactions on Power Systems,* vol.15, no.4, pp.1184-1190, Nov 2000

[9] Szumanowski, A.; Piorkowski, P.; Chang, Y.; , "Batteries and Ultracapacitors Set in Hybrid Propulsion System," *International Conference on Power Engineering, Energy and Electrical Drives, POWERENG 2007.*, pp.122-127, 12-14 April 2007

[10] L. Piegari, P. Tricoli: “A Control Algorithm of Power Converters in Smart-Grids for Providing Uninterruptible Ancillary Services”, *Harmonics and quality of power 21st IEEE International Conference on,* September 2010

[11] IEC 61000-3-3, Limitation of voltage changes, voltage fluctuation and flicker in public low voltage supply systems, for equipment with rated current less or equal to 16A per phase and not subject to conditional connection, June 2008

[12] IEC 61000-3-11 Limitation of voltage changes, voltage fluctuation and flicker in public low voltage supply systems - Equipment with rated current less or equal to 75A per phase and subject to conditional connection, August 2008

VII. BIOGRAPHIES

Samuele Grillo (M’05) is was born in 1980. He received the “Laurea” degree in electronic engineering in 2004 and the Ph.D. degree in power systems in 2008 both from the University of Genoa, Genoa, Italy. Currently he is Assistant Professor with the Department of Electrical Engineering, Politecnico di Milano, Milan, Italy. His research interests include smart grids, optimization and control techniques and neural networks and their application to power systems (i.e., security assessment, load and production forecast, local and small generation management).

Vincenzo Musolino received the M.S. degree in electrical engineering in 2007 from the Politecnico di Milano, Milano, Italy. Actually he is a PhD student in Electrical Engineering at the Electrical Department of the Politecnico di Milano. His research interests include electrical storage devices, power electronics and distributed generation.

Luigi Piegari (M’04) was born in 1975. He received the M.S. and Ph.D. degrees in electrical engineering from the University of Naples Federico II, Naples, Italy, in 1999 and 2003, respectively. Currently, he is an Assistant Professor with the Department of Electrical Engineering, Politecnico di Milano, Milan, Italy. His current research interests include electrical machines, high-efficiency power electronic converters, renewable energy sources, and electrical supplies and cableway plants.

Enrico Tironi received the M.S. degree in Electrical Engineering from the Politecnico di Milano, Italy, in 1972. In 1972 he joined the Department of Electrical Engineering of the Politecnico di Milano where he is Full Professor at present. His areas of research include power electronics, power quality and distributed generation. He is a member of Italian Standard Authority (C.E.I.), Italian Electrical Association (A.E.I.) and Italian National Research Council (C.N.R.) group of Electrical Power System