ELSEVIER

Journal of Power Sources 67 (1997) 193–200

JOURNAL OF POWER SOURCES

A strategy for low-cost utility connection of battery energy storage systems

S. Wall *, D. McShane

Wavedriver Ltd., New Cambridge House, Litlington, Hertfordshire SG8 6TA, UK

Received 14 August 1996; accepted 30 December 1996

Abstract

Battery energy storage is a well-known concept that has applications within the electricity supply industry. In a battery energy storage system (BESS), the d.c. energy in the batteries is exchanged with the d.c. utility using a power conversion system (PCS). The development of a generic low-cost PCS is identified as being critical to commercial viability of battery energy storage. The paper presents commercial and functional advantages of using a modular approach to power conversion in a BESS. Dynamic models are developed for both single and networked power converters. These are used to demonstrate the technical feasibility of the modular approach. The Wavedriver PCS is presented. This uses a modular network of generic power converters to provide higher functionality. Each power converter incorporates a higher level of systems integration than is usually present in a traditional PCS. This approach changes the balance on the commercial viability of energy storage systems. © 1997 Published by Elsevier Science S.A.

Keywords: Batteries; Energy storage systems; Power conversion; Dynamic modelling; Networks

1. Introduction

A battery energy storage system (BESS) can be sub-divided into three sections: (i) the battery and associated management equipment; (ii) a power conversion system (PCS), and (iii) the balance-of-plant (BOP). A diagrammatic representation of these components is shown in Fig. 1. The PCS performs the basic function of exchanging energy between the d.c. storage device and the a.c. utility. The remainder of the utility interface, all the ancillary systems and the physical housing of the BESS make up the BOP.

BESS installations range in size from 200 kW to 20 MW, and are connected at various voltage levels within the distribution network dependent on their application. Presently, BESS costs range from US$ 1000/kW to US$ 800/kW for 2 h storage. If the system costs can be reduced to US$ 600/kW for a 3 h storage system, then they are set for widespread take up within the industry [1].

* Corresponding author. e-mail: simonw@wavedriver.co.uk.

2. Reducing the installation cost of a BESS

Consider the potential for cost reduction in the three elements of a BESS.

1. *The battery.* Battery technology for storage applications is approaching maturity. The principal opportunity for cost reduction will come from volume production and the use of active battery-management systems to increase lifetime and reduce maintenance overheads.
2. *The balance-of-plant.* The BOP includes the housing of the battery storage system, the utility connection transformer, a.c. and d.c. contactors, circuit breakers, other protective elements and all ancillary components. Standard, high volume, low margin industrial equipment is used. The only opportunity for cost reduction comes from the elimination of some of these devices by inclusion of their functionality within the PCS device.
3. *The power conversion system.* The PCS handles power transfer between the utility and the battery. A high degree of intelligence is inherent in these systems to manage the real-time control of power flow into and out of the battery energy store. In a typical BESS, the PCS

0378-7753/97/$17.00
PII S0378-7753(97)02551-2

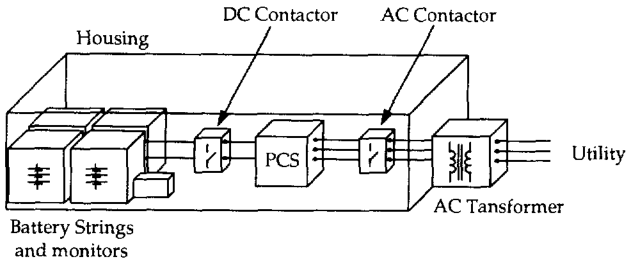

Fig. 1. Components of a battery energy-storage system.

is a high power unit manufactured in low volume. The margin must be high to cover the substantial development cost. To gain the benefits of mass production, it is proposed to use many low power units connected in parallel. This approach will also increase the scaleability of the BESS. The intelligence and data acquisition inherent in the PCS can be used to incorporate some of the required utility protection features, resulting in a direct reduction of BOP costs. In the UK, for example, features such as G.59/1 protection are easily accommodated within the PCS system. The PCS element is the key to commercial success for battery energy storage.

3. Commercial advantages of modular power conversion systems

A traditional BESS usually employs a large 'custom' PCS. These devices do not lend themselves to volume manufacture and will always be expensive with regards to manufacture and maintenance. Modular PCS devices, which can be networked to achieve the same power ratings, benefit through the economies of mass production, and can provide a solution that has better redundancy, reliability, and efficiency. The modular approach also permits flexible siting arrangements for the BESS, portability and the opportunity to upgrade easily ratings as required.

The cost advantages associated with modularity are highlighted in Table 1. Although the up-front development cost and the investment in manufacturing equipment have not been included, the cost argument for modular PCSs is a powerful one. When one consides that the PCS accounts traditionally for over 30% of the cost of a storage scheme, the modular approach can have significant impact on the economic viability of a BESS.

Additional savings can be made by exploiting the intelligence and data acquisition inherent in the PCS to reduce the cost associated with the BOP and system integration components. Whilst this may produce a marginal increase on the cost of the PCS, absorbing these elements within the functionality of the PCS can have a dramatic reduction on the cost of the BESS installation.

4. Functional advantages of modular power conversion systems

A modular PCS is composed of many small power converters networked in parallel. Provided that the individual units operate with a sufficient degree of autonomy, the size of the network can be rescaled dynamically. Clearly, this offers the advantages of redundancy and on-line maintenance. High efficiency can be maintained at low power throughputs, because only the minimum required number of power converters need be energised. In this way all the power converters energized at any one time will be operating near to their rated power levels, regardless of the total power throughput of the PCS.

Further advantages are possible if the switching patterns of the individual power converters in the network are synchronized and interleaved in phase. To a first approximation, this approach can be used to eliminate the first $(n-1)$ harmonics of the switching frequency from the a.c. line currents of a network of n parallel-connected power converters. The common-mode noise and ground isolation requirements on the d.c. side of the power converter network is also reduced by a factor of $(n-1)$.

For a BESS, a modular approach to power conversion has been shown to have both commercial and functional advantages. It remains to show that the approach is technically feasible. In order to do this, it is necessary to develop dynamic models of a generic PCS, both in stand-alone operation and as part of a parallel network.

5. Dynamic model of a stand-alone power conversion system

A typical PCS is based upon the three-phase, utility-connected, voltage-source inverter depicted in Fig. 2. The d.c. link voltage, V_{dc}, interfaces with the utility, V_{g1} to V_{g3}, via a pulse-width modulated (PWM) full bridge of switch-

Table 1
Cost comparison between single and modular power conversion systems

	Single large GTO converter	Modular IGBT converter
Cost per kW	US$ 100 (best)	US$ 50 (in volume)
Cost of assembly	high — hand assembled	low — automated assembly
Cost of installation	high — engineer tested	low — automated testerand test

ing devices and a coupled line inductor, M. The lumped circuit resistances, R_1 to R_3, have been included to model the circuit losses, e.g., winding and magnetic losses in M and conduction losses in the switch/diode anti-parallel pairs of the full bridge.

The switch states are described by the zero biased logic functions, D_1, D_2, $D_3 \in \{-1/2, 1/2\}$. In the kth leg of the bridge, if $D_k = 1/2$ the upper switch is on and the lower switch is off. The situation is reversed when $D_k = -1/2$. The circuit equation can be expressed in terms of the switch states and the mid-point voltage of the DC link, V_m:

$$\begin{bmatrix} L_1 & M_{12} & M_{13} \\ M_{21} & M_2 & M_{23} \\ M_{31} & M_{32} & L_3 \end{bmatrix} \begin{bmatrix} \dot{I}_1 \\ \dot{I}_2 \\ \dot{I}_3 \end{bmatrix} = -\begin{bmatrix} R_1 & 0 & 0 \\ 0 & R_2 & 0 \\ 0 & 0 & R_3 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} + V_{dc} \begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} - \begin{bmatrix} V_{g1} \\ V_{g2} \\ V_{g3} \end{bmatrix} + V_m \tag{1}$$

$$M \cdot \dot{I} = -R \cdot I + V_{dc} \cdot D - V_g + V_m \tag{1a}$$

Three typical inductor configurations for a three-phase systems are:
1. three single-phase inductors, $M = M_{uc}$;
2. one standard three-phase inductor, $M = M_{3\phi}$;
3. one three-phase common-mode inductor, $M = M_{cm}$.

$$M_{uc} = \begin{bmatrix} L_1 & 0 & 0 \\ 0 & L_2 & 0 \\ 0 & 0 & L_3 \end{bmatrix} \tag{2a}$$

$$M_{3\phi} = L_s \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ -\frac{1}{2} & 1 & -\frac{1}{2} \\ -\frac{1}{2} & -\frac{1}{2} & 1 \end{bmatrix} \tag{2b}$$

$$M_{cm} = L_{cm} \begin{bmatrix} 1 & \frac{1}{n_1} & \frac{1}{n_2} \\ \frac{1}{n_1} & \frac{1}{n_1^2} & \frac{1}{n_1 n_2} \\ \frac{1}{n_2} & \frac{1}{n_1 n_2} & \frac{1}{n_2^2} \end{bmatrix} \tag{2c}$$

Previous attempts to model the utility connected voltage-source inverter have concentrated on the special case where three, equal value, single-phase inductors are used and the resistance associated with each phase is equal, i.e., $M = M_{uc}$, $L_1 = L_2 = L_3 = L_{sp}$ and $R_1 = R_2 = R_3 = R_{sp}$. For

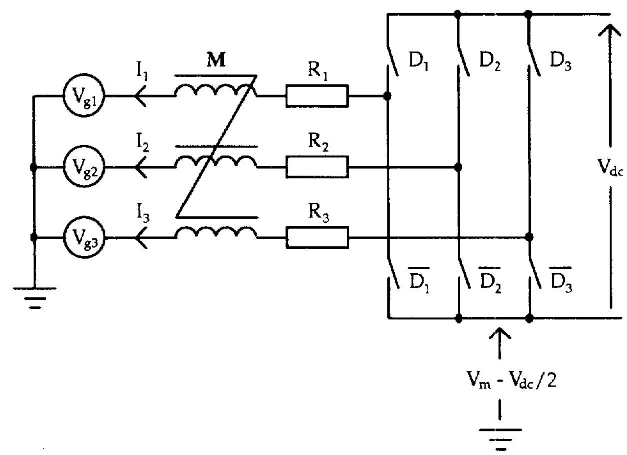

Fig. 2. Circuit diagram for a utility-connected, voltage-source inverter.

this type of system the circuit Eq. (1) can be reduced to a much simple equivalent

$$L_{sp} \begin{bmatrix} \dot{I}_1 \\ \dot{I}_2 \\ \dot{I}_3 \end{bmatrix} = -R_{sp} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} + V_{dc} \begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} - \begin{bmatrix} V_{g1} \\ V_{g2} \\ V_{g3} \end{bmatrix} + V_m \tag{3}$$

The special case circuit Eq. (3) can readily be converted to a state-space system equation [2,3]. The approach used involves finding an expression for V_m by combining Eq. (3) and the Kirchoff current balance, $I_1 + I_2 + I_3 = 0$. The special case state-space equation can then be found by substitution

$$V_m = \frac{1}{3}\left(\sum_{k=1}^{3} V_{gk} - V_{dc} \sum_{k=1}^{3} D_k \right) \tag{4}$$

$$\begin{bmatrix} \dot{I}_1 \\ \dot{I}_2 \\ \dot{I}_3 \end{bmatrix} = -\frac{R_{sp}}{L_{sp}} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} + \frac{1}{L_{sp}} \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3} & -\frac{1}{3} & \frac{2}{3} \end{bmatrix} \times \left[V_{dc} \begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} - \begin{bmatrix} V_{g1} \\ V_{g2} \\ V_{g3} \end{bmatrix} \right] \tag{5}$$

In the general case, the Kirchoff current balance, $I_1 + I_2 + I_3 = 0$, cannot be combined readily with Eq. (1) to produce a simple expression for V_m. Attempts to extract a state-space equation are also hampered by the possible singularity of M. For example, although it is highly desirable to use a standard three-phase inductor, $M_{3\phi}$ is singular.

To eliminate V_m from the system equations and combat the possible singularity of M the following approach has been developed. The rows of Eq. (1) are differenced resulting in a line to line representation of the system. This does not include the d.c. link mid point voltage, V_m

$$\begin{bmatrix} L_1 - M_{21} & M_{12} - L_2 & M_{13} - M_{23} \\ M_{21} - M_{31} & L_2 - M_{32} & M_{23} - L_3 \\ M_{31} - L_1 & M_{32} - M_{12} & L_3 - M_{13} \end{bmatrix} \begin{bmatrix} \dot{I}_1 \\ \dot{I}_2 \\ \dot{I}_3 \end{bmatrix} = - \begin{bmatrix} R_1 & -R_2 & 0 \\ 0 & R_2 & -R_3 \\ -R_1 & 0 & R_3 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} + V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} - \begin{bmatrix} V_{g12} \\ V_{g23} \\ V_{g31} \end{bmatrix} \quad (6)$$

The third row of the line to line circuit equation is linearly dependent on the other two. Therefore, to characterize fully the circuit, one of the rows must be replaced with and independent circuit equation. One suitable choice is the derivative form of the Kirchoff current balance, $I_1 + I_2 + I_3 = 0$.

$$\begin{bmatrix} L_1 - M_{21} & M_{12} - L_2 & M_{13} - M_{23} \\ M_{21} - M_{31} & L_2 - M_{32} & M_{23} - L_3 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} \dot{I}_1 \\ \dot{I}_2 \\ \dot{I}_3 \end{bmatrix} = - \begin{bmatrix} R_1 & -R_2 & 0 \\ 0 & R_2 & -R_3 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} + V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} - \begin{bmatrix} V_{g12} \\ V_{g23} \\ 0 \end{bmatrix} \quad (7)$$

$$M^* \cdot \dot{I} = -R^* \cdot I + V_{dc} \cdot \Lambda \cdot D - V_g^* \quad (7a)$$

If M^* is singular then one or more of its rows will be linearly dependent on the other rows. Therefore, the individual rows of Eq. (7) must show an equivalent linear relationship. It is possible to equate the appropriate linear combinations of the right-hand sides of Eq. (7). This produces expressions for the instantaneous currents, I_1 to I_3, in terms of R_1 to R_3, D_1 to D_3, V_{g12}, V_{g23} and V_{dc}.

A physical interpretation of the singularity of M^* is that the line reactor is not able to support the voltage difference between V_{gk} and V_{wk} at all times. The remaining voltage difference will be supported as a resistive drop across R_k, which is contrary to the design requirements of a switched-mode converter. Therefore, it can be assumed that M^* will be invertible in any practical realization of the utility connected voltage-source inverter. In this case, the generalized state-space equation follows directly

$$\dot{I} = [M^*]^{-1} \cdot [-R^* \cdot I + V_{dc} \cdot \Lambda \cdot D - V_g^*] \quad (8)$$

Note: M_{uc}^* and $M_{3\phi}^*$ are both invertible, but M_{cm}^* is singular. The unsuitability of a common-mode choke to smooth the differential PWM signals generated by a voltage-source inverter should come as no surprise.

The state-space model developed above allows input current spectra to be predicted for the generalized class of utility-connected voltage-source inverters, with rectangular PWM controlled switches. Eq. (10) is suitable for direct entry into most simulation packages. This state-space equation applies the current balance, $I_1 + I_2 + I_3 = 0$, in derivative form. Therefore, an error in the current balance can be built up due to numerical round-off errors. To prevent cumulative round-off errors, the current balance, $I_1 + I_2 + I_3 = 0$, should be applied to result of the numerical integration, at each step of the simulation.

5.1. Example

A model of the Wavedriver Power Conversion System was developed on the Simulink platform using the analysis given above. The simulated line current spectrum was

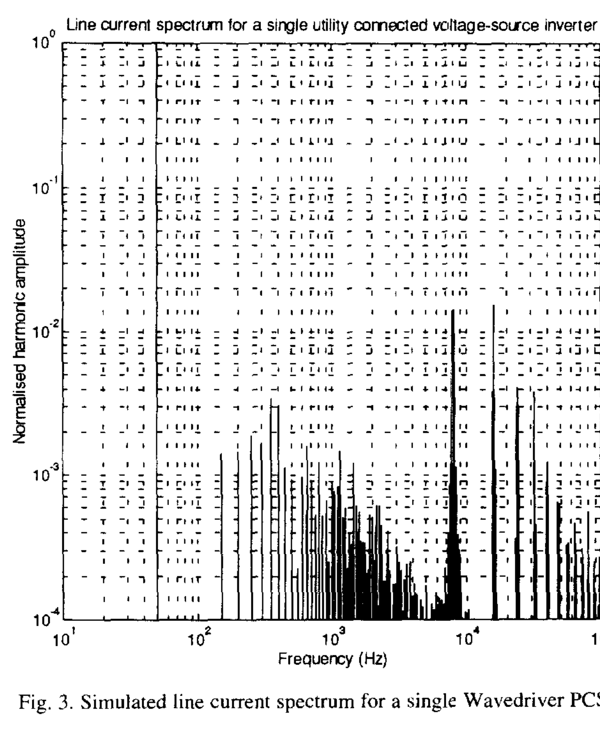

Fig. 3. Simulated line current spectrum for a single Wavedriver PCS.

found to be that given in Fig. 3. The key system parameters for the simulation were as follows:

d.c. link voltage	400 V
a.c. line voltage	208 V
a.c. line current	100 A
switching pattern	space vector modulated PWM at 8 kHz
line reactor	standard three-phase reactor
	$M = M_{3\phi}$ (L_s = 200 μH) in series
	with a three-phase common-mode
	choke of 100 μH

6. Dynamic model for a parallel network of power conversion systems

It is proposed to build higher utility-connected voltage-source inverters by using the single units as building blocks connected in parallel. The connection diagram for a network of n individual systems acting in parallel is depicted in Fig. 4.

In a parallel network, it is possible to have currents that circulate between the individual units. As a result, each unit can have unbalanced line currents, i.e., for the kth system $I_1^k + I_2^k + I_3^k \neq 0$. The circuit equation for the kth parallel connected unit is the same as for a single utility-connected voltage-source inverter.

$$\begin{bmatrix} L_1^k & M_{12}^k & M_{13}^k \\ M_{21}^k & L_2^k & M_{23}^k \\ M_{31}^k & M_{32}^k & L_3^k \end{bmatrix}\begin{bmatrix} \dot{I}_1^k \\ \dot{I}_2^k \\ \dot{I}_3^k \end{bmatrix} = -\begin{bmatrix} R_1^k & 0 & 0 \\ 0 & R_2^k & 0 \\ 0 & 0 & R_3^k \end{bmatrix}\begin{bmatrix} I_1^k \\ I_2^k \\ I_3^k \end{bmatrix} + V_{dc}\begin{bmatrix} D_1^k \\ D_2^k \\ D_3^k \end{bmatrix} - \begin{bmatrix} V_{g1} \\ V_{g2} \\ V_{g3} \end{bmatrix} + V_m \qquad (9)$$

$$M^k \cdot \dot{I}^k = -R^k \cdot I^k + V_{dc} \cdot D^k - V_g + V_m \qquad (9a)$$

If M^k is singular, then one or more of its rows will be linearly dependent on the other rows. Therefore, the individual rows of Eq. (9) must show an equivalent linear relationship. It is possible to equate the appropriate linear combinations of the right-hand sides of Eq. (9). This produces an expression for V_m in terms of, I_1^k to I_3^k, R_1^k to R_3^k, D_1^k to D_3^k, V_{g1} to V_{g3} and V_{dc}. If more than one power converter has a singular M^k, then the line currents in each can be found by equating all the expressions for V_m.

A physical interpretation of the singularity of two or more M^k is that the line reactors are not able to support the voltage difference between V_{gj} and V_{wj}^k at all times. The remaining voltage difference will be supported as a resistive drop across R_j^k, which is contrary to the design requirements of a switched-mode converter. Therefore, it can be assumed that, for a practical network system, no more than one of the power converters will have a singular M^k.

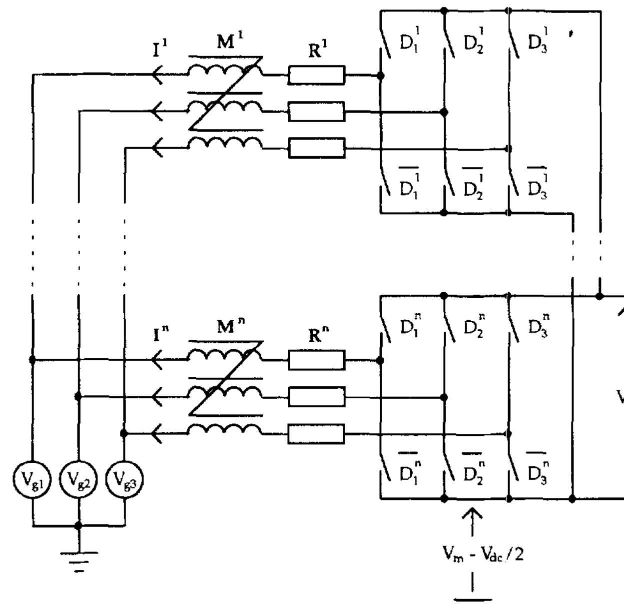

Fig. 4. Parallel connected, utility-connected voltage-source inverters.

In the case of a single utility connected voltage-source inverter, the line-to-line circuit equations were combined with a current balance to eliminate V_m and produce the revised circuit Eq. (7). This approach is not possible for a parallel network because no current balance exists for each individual converter. Instead, the current balance equation applies to the whole network

$$\sum_{k=1}^{n} \left(I_1^k + I_2^k + I_3^k \right) = 0 \qquad (10)$$

To apply the overall current balance of Eq. (10), expressions must be found for the line current in each power converter in the network. A first step is to convert the n circuit equations into Laplace form. This enables all line current terms to be grouped together

$$\begin{bmatrix} sL_1^k + R_1^k & sM_{12}^k & sM_{13}^k \\ sM_{21}^k & sL_2^k + R_2^k & sM_{23}^k \\ sM_{31}^k & sM_{32}^k & sL_3^k + R_3^k \end{bmatrix}\begin{bmatrix} I_1^k \\ I_2^k \\ I_3^k \end{bmatrix}(s) = \left[V_{dc}\begin{bmatrix} D_1^k \\ D_2^k \\ D_3^k \end{bmatrix} \right](s) - \begin{bmatrix} V_{g1} \\ V_{g2} \\ V_{g3} \end{bmatrix}(s) + V_m(s) \qquad (11)$$

Consider the special case where all the power converters are designed such that the circuit time-constants and line reactor coupling factors are similar, i.e., the line reactors have the same geometry, but may differ in size and value. For this relatively general class of parallel network the difference between each power converter can be characterized by a single base inductance value, L^k.

6.1. Special case 1

- $M^k = L^k\Psi$
- $R_1^k/L^k = 1/T_1,\ R_2^k/L^k = 1/T_2,\ R_3^k/L^k = 1/T_3$

$$L^k \begin{bmatrix} \alpha_{11}\left(s+\frac{1}{T_1}\right) & \alpha_{12}s & \alpha_{13}s \\ \alpha_{21}s & \alpha_{22}\left(s+\frac{1}{T_2}\right) & \alpha_{23}s \\ \alpha_{31}s & \alpha_{32}s & \alpha_{33}\left(s+\frac{1}{T_2}\right) \end{bmatrix} \times \begin{bmatrix} I_1^k \\ I_2^k \\ I_3^k \end{bmatrix}(s) = \begin{bmatrix} V_{dc}\begin{bmatrix} D_1^k \\ D_2^k \\ D_3^k \end{bmatrix}\end{bmatrix}(s) - \begin{bmatrix} V_{g1} \\ V_{g2} \\ V_{g3} \end{bmatrix}(s) + V_m(s) \tag{12}$$

$$L^k \cdot A(s) \cdot \dot{I}^k(s) = \left[V_{dc} \cdot D^k\right](s) - V_g(s) + V_m(s) \tag{12a}$$

$$\begin{aligned} &Det\left(L^k A(s)\right) \\ &= s^3 Det(M^k) + s^2\left(R_1^k\left(L_2^k L_3^k - M_{23}^k M_{32}^k\right)\right. \\ &\quad + R_2^k\left(L_1^k L_3^k - M_{13}^k M_{31}^k\right) + \left.R_3^k\left(L_1^k L_2^k - M_{12}^k M_{21}^k\right)\right) \\ &\quad + s\left(L_1^k R_2^k R_3^k + L_2^k R_1^k R_3^k + L_3^k R_1^k R_2^k\right) + R_1^k R_2^k R_3^k \end{aligned}$$

In a real system

$R_1^k \geq 0,\ R_2^k \geq 0,\ R_3^k \geq 0,\ L_1^k \geq 0$

$L_2^k \geq 0,\ L_3^k \geq 0\ L_\alpha^k L_\beta^k \geq M_{\alpha\beta}^k M_{\beta\alpha}^k,\ Det(M^k) \geq 0,\ L^k > 0$

If Ψ is singular, all M^k will be singular. It has already been established that no more than one of the parallel connected power converters may have a singular M^k. So in any network ($n > 1$) where $M^k = L^k\Psi$, all M^k are non-singular. Therefore, $Det(L^k \cdot A(s)) \neq 0$ and $A(s)$ can be inverted to yield an expression for the line currents in each utility-connected voltage-source inverter

$$\dot{I}^k(s) = A^{-1}(s)\left[\frac{1}{L^k}\left(\left[V_{dc} \cdot D^k\right](s) - V_g(s) + V_m(s)\right)\right] \tag{13}$$

The d.c. link, mid-point voltage, V_m, can be found by application of the overall line current summation given in Eq. (10)

$$V_m(s) = \frac{\sum_{j=1}^{3}\left(g_j(s)\sum_{k=1}^{n}\left[\frac{1}{L^k}\left(V_{gj}(s) - \left[V_{dc} \cdot D_j^k\right](s)\right)\right]\right)}{\left(g_1(s)+g_2(s)+g_3(s)\right)\sum_{k=1}^{n}\frac{1}{L^k}} \tag{14}$$

$$\left[g_1(s)\ g_2(s)\ g_3(s)\right] = [1\,1\,1] \cdot A^{-1}(s) \tag{15}$$

Using a symbolic algebra package, an expression for $V_m(s)$ has been found for the general sub-class of parallel systems described by special case 1. The result is not repeated here due to space restrictions, but can be used in most state-space simulation packages to set up automatically the transfer-function coefficients. To provide some further insight, consider the very common sub-class of special case 1.

6.2. Special case 2

- $R_1^k = R_2^k = R_3^k = L^k/T$
- $L_1^k = L_2^k = L_3^k = L^k$
- $M_{12}^k = M_{21}^k = M_{13}^k = M_{31}^k = M_{23}^k = M_{32}^k = \beta L^k$

$$A(s) = B(s) = \begin{bmatrix} \left(s+\frac{1}{T}\right) & \beta s & \beta s \\ \beta s & \left(s+\frac{1}{T}\right) & \beta s \\ \beta s & \beta s & \left(s+\frac{1}{T}\right) \end{bmatrix}$$

$$\Rightarrow g_1(s) = g_2(s) = g_3(s) = \frac{1}{(2\beta+1)s + \frac{1}{T}}$$

$$V_m = \frac{\sum_{k=1}^{n}\left[\frac{1}{L^k}\left(\sum_{j=1}^{3} V_{gj} - V_{dc}\sum_{j=1}^{3} D_j^k\right)\right]}{3\sum_{k=1}^{n}\frac{1}{L^k}} \tag{16}$$

Once the d.c. link, mid-point voltage is known, the state-space equation for the entire network follows directly from the circuit Eq. (9). Any state-space simulation package capable of utilizing the transfer-function model for V_m can be used.

6.3. General case

$$\dot{I}^k = \left[M^k\right]^{-1}\left[-R^k I^k + V_{dc} D^k - V_g + V_m\right] \tag{17}$$

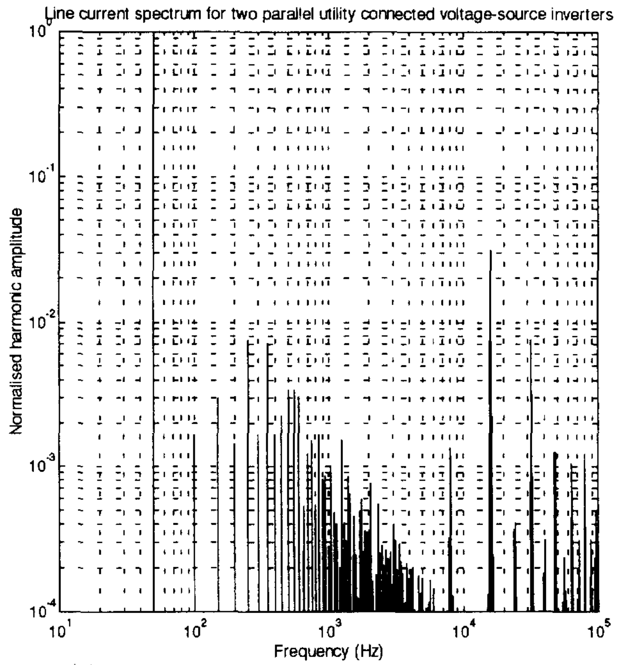

Fig. 5. Simulated line current spectra for two parallel Wavedriver PCSs.

6.4. Special case 1

$$\dot{I}^k = \Psi^{-1}\left[-\begin{bmatrix}\frac{1}{T_1} & \frac{1}{T_2} & \frac{1}{T_3}\end{bmatrix}^T I^k + \frac{1}{L^k}\left(V_{dc} D^k - V_g + V_m\right)\right] \tag{18}$$

6.5. Special case 2

$$\begin{bmatrix}\dot{I}_1^k \\ \dot{I}_2^k \\ \dot{I}_3^k\end{bmatrix} = \frac{1}{(1+2\beta)(1-\beta)}\begin{bmatrix}1+\beta & -\beta & -\beta \\ -\beta & 1+\beta & -\beta \\ -\beta & -\beta & 1+\beta\end{bmatrix} \times \left[-\frac{1}{T}\begin{bmatrix}I_1^k \\ I_2^k \\ I_3^k\end{bmatrix} + \frac{1}{L^k}\left(V_{dc}\begin{bmatrix}D_1^k \\ D_2^k \\ D_3^k\end{bmatrix} - \begin{bmatrix}V_{g1} \\ V_{g2} \\ V_{g3}\end{bmatrix} + V_m\right)\right] \tag{19}$$

6.6. Example

A model of two parallel-connected Wavedriver PCSs was developed on the Simulink platform using the analysis given above. The switching periods of the units were set to be interleaved, i.e., 180° out of phase. The simulated line current spectrum was found to be that given in Fig. 5. The key system parameters for the simulation were the same as those used to produce Fig. 3.

6.7. Conclusions

The parallel connection of modular PCS units is technically feasible. Standard three-phase line reactors cannot be used, however, unless they are augmented with a common-mode choke. It was demonstrated that harmonic cancellation is possible in parallel networks, provided that the switching periods of the units are interleaved.

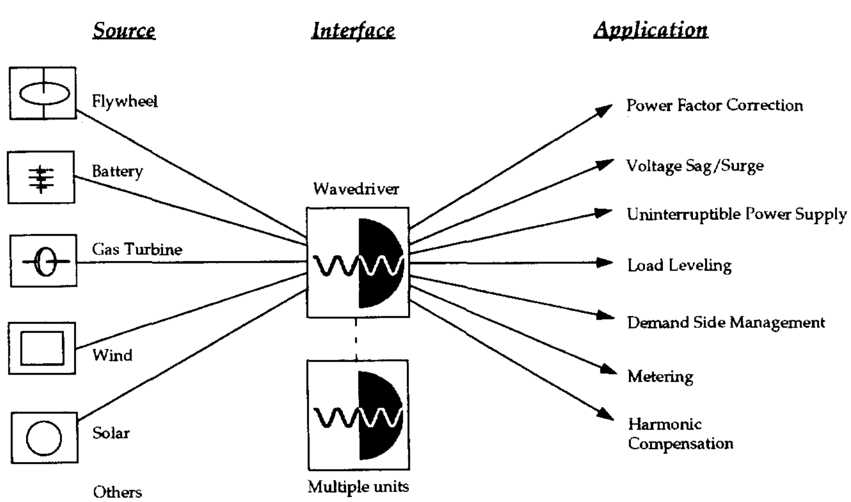

Fig. 6. The generic power conversion system.

7. Generic power conversion systems — increased functionality, reduced cost

The diversity of application for the energy storage system can be increased if the PCS design includes a flexible modular based software platform. To realize the opportunities for battery energy storage, it is important to ask the question: what are the features of the ideal power conversion system? The response from the utility industry having implemented storage systems is in our experience:

The ideal PCS is ···
- inexpensive
- efficient
- scaleable to application requirements (modular)
- easily integrated into the power system
- flexible for multiple use
- autonomous
- compact

The flexible requirement enables the PCS to be a generic device capable of interfacing other sources of energy storage or alternative generation to the utility to perform a range of applications. Spanning diverse applications from different sources with the one power coupler creates a large volume demand for the PCS unit in a segmented market. This approach gains from economies of scale and provides a route to low-cost manufacture of the PCS system, reducing its cost for battery energy storage systems. In addition, the diversity of application for the PCS introduces robustness of price as the systems are somewhat insensitive to changes within one area of market application.

The concept of a generic PCS is illustrated in Fig. 6.

8. The wavedriver system — a generic power coupling device

The Wavedriver system is a four-quadrant power converter of up to 100 kVA rating. The device is based on a sophisticated IGBT inverter, following a PWM regime developed in real time according to a modified space-vector method. It is liquid cooled which enables the unit to be compact and lightweight. Particular effort has been made in its design for mass production. The basic capabilities of the power electronics are greatly enhanced by the features of the Wavedriver software system. Wavedriver have provided an operating platform that allows the same unit to be configured for many applications, or indeed, to run several applications concurrently. The Wavedriver also includes a substantial communication's suite that enables network operation of multiple units from a centralized controller. This approach has many advantages for utilities with regards to power quality, the key benefits of which are:
- one device can be used for many applications
- the same device may be simply reprogrammed and deployed for another duty
- the system is modular and installations can be cost effectively sized for application
- the system is small and easy to site
- the system is autonomous but can be controlled remotely
- mass production of one hardware device is lower cost than customized solutions

9. Conclusions

By applying advanced software, hardware and communications methods, Wavedriver Limited has developed a new type of power processing system — the 'Wavedriver' — which provides a route to widespread application of battery energy storage.

The generic and modular nature of the Wavedriver system allows the diverse market of energy storage and alternative generation to use one type of device for connection to the utility at all power levels. This approach enables volume manufacture of the device and, hence, reduces the cost impact of the PCS on the battery energy storage system.

References

[1] J. Hurwitch, Commercial readiness of battery storage, *Technologies, Markets, and Projects' Utility Battery Storage Conf., 4–5 June 1996, Coventry, UK.*

[2] R. Wu, S.B. Dewan and G.R. Slemon, *IEEE Ind. Appl. Conf. Rec.*, (1988) 706–711.

[3] R. Wu, S.B. Dewan and G.R. Slemon, *IEEE Trans. Ind. Appl., 27* (1991) 355–363.