COMPONENT MINIMIZED MULTI-DRIVE SYSTEMS BASED ON TWO-PHASE AND THREE-PHASE MACHINES

O. I. da Silva[1,2], C. B. Jacobina[1], E. C. dos Santos Jr.[1] and A. M. N. Lima[1]
[1]LEIAM - Dep. de Eng. Elétrica - CCT - UFCG - Caixa Postal 10.105
58109-970 Campina Grande, PB - Brasil
[2]CEFET - PE
50000-000 Recife - PE - Brazil

Abstract: **This paper compares two component minimized multiple three-phase and two-phase *ac* drive systems. Topology A uses two-phase machines, while Topology B uses three-phase machines. Both topologies uses multiple two-leg inverter associated with a same shared leg and have complementary voltage and current rating performance. Main characteristics of the drive systems are presented together experimental results.**

Keywords **Multiple three-phase drive, Multiple two-phase drive**

I. INTRODUCTION

A standard *ac* drive system is constituted by an input rectifier, a capacitor bank for the *dc*-bus, a voltage source inverter, an electrical machine and a microcomputer based controller. In industrial applications where it is required to drive multiple electrical machines, the direct solution consists in replicating such standard configuration. One alternative for reducing costs in this case is to use a common *dc*-bus for all drive systems installed in the shop-floor of the plant. Furthermore, to further reduce the installation costs one can use converter topologies with minimized number of power switching devices [3], [1], [12], [5], [4], [9], [11], [10]. This article investigates different *ac* drive configurations where these two approaches are jointly employed to provide a significant reduction in the number of power devices in comparison with the direct solution in which the standard configuration is simply replicated. This paper examines two component minimized multiple *ac* drive systems in which all the inverters share a connection to an extra-leg as shown in Figs. 1 and 2. Configuration A uses [6] while configuration B uses three-phase machines [8]. Both configurations use multiple two-leg inverter topologies with a same shared leg. A more reduced switch count system can be obtained by sharing the mid-point capacitor bank in the *dc*-bus [8], but that configuration was not considered in this paper due to the problems associated with the *ac* current flowing through the capacitor.

II. MACHINE DRIVE SYSTEMS

Fig. 1 presents configuration A, that has an input rectifier, a capacitor bank for the *dc*-bus and n two-phase machines supplied by n voltage source inverters (switches q_{al}, $\overline{q}_{al}$, q_{bl} and $\overline{q}_{bl}$, for $l = 1$ to n, and q_c and $\overline{q}_c$). In this configuration one extra leg is shared by all inverters with the neutral of each machine connected to it. Fig. 2 shows configuration B, that uses n three-phase machines where the third phase of each one is connected to the shared leg. From now on, in all the expressions where the subscript l appears it must be understood that it refers to the all n machines and then it varies from 1 to n.

The conduction state of all the switches will be represented by an homonymous binary variable q_{al}, $\overline{q}_{al}$, q_{bl}, $\overline{q}_{bl}$, q_c and $\overline{q}_c \in \{0,1\}$, where $q = 1$ indicates a closed switch while $q = 0$ indicates an open one. Pairs $q_{al} - \overline{q}_{al}$, $q_{bl} - \overline{q}_{bl}$ and $q_c - \overline{q}_c$ are complementary and therefore $\overline{q}_{al} = 1 - q_{al}$, $\overline{q}_{bl} = 1 - q_{bl}$ and $\overline{q}_c = 1 - q_c$.

III. PWM CONTROL - CONFIGURATION A

Considering the configuration shown in Fig. 1, the machine voltages v_{sal} and v_{sbl}, are expressed as

$$v_{sal} = v_{al0} - v_{c0} = (q_{al} - q_c)E \quad (1)$$
$$v_{sbl} = v_{bl0} - v_{c0} = (q_{bl} - q_c)E \quad (2)$$

where E is the *dc*-bus voltage, v_{al0} , v_{bl0} and v_{c0} are the machine voltages referred to the *dc*-bus midpoint ($'0'$) (i.e., the mid-point voltages).

If the desired machines phase voltages are given by v^*_{sal} and v^*_{sbl}, then the voltages referred to the capacitor bank midpoint may be expressed by

$$v^*_{al0} = v^*_{sal} + v^*_{c0} \quad (3)$$
$$v^*_{bl0} = v^*_{sbl} + v^*_{c0}. \quad (4)$$

Note that these equations cannot be solved unless v^*_{c0} is specified. Equations (3) and (4) can be formulated as

$$v^*_{al0} = v^*_{sal} + v^*_{\mu} \quad (5)$$
$$v^*_{bl0} = v^*_{sbl} + v^*_{\mu} \quad (6)$$
$$v^*_{c0} = v^*_{\mu}. \quad (7)$$

The PWM control can be done in accordance with one of the two methods presented next.

Method I: Local apportioning factor

The voltage v^*_{μ} can be determined by taking into account the local apportioning factor μ_j of a j^{th} machine. In this case $v^*_{\mu} = v^*_{\mu j}$, where $v^*_{\mu j}$ is given by

$$v^*_{\mu j} = E(\mu_j - \frac{1}{2}) - \mu_j v^*_{j\,\max} + (\mu_j - 1)v^*_{j\,\min}. \quad (8)$$

where $v^*_{j\,\max} = \max V_j$ and $v^*_{j\,\min} = \min V_j$, where $V_j = \{v^*_{saj}, v^*_{sbj}, 0\}$.

Expression (8) was derived by using the same approach employed to derive the equivalent one for the three-phase

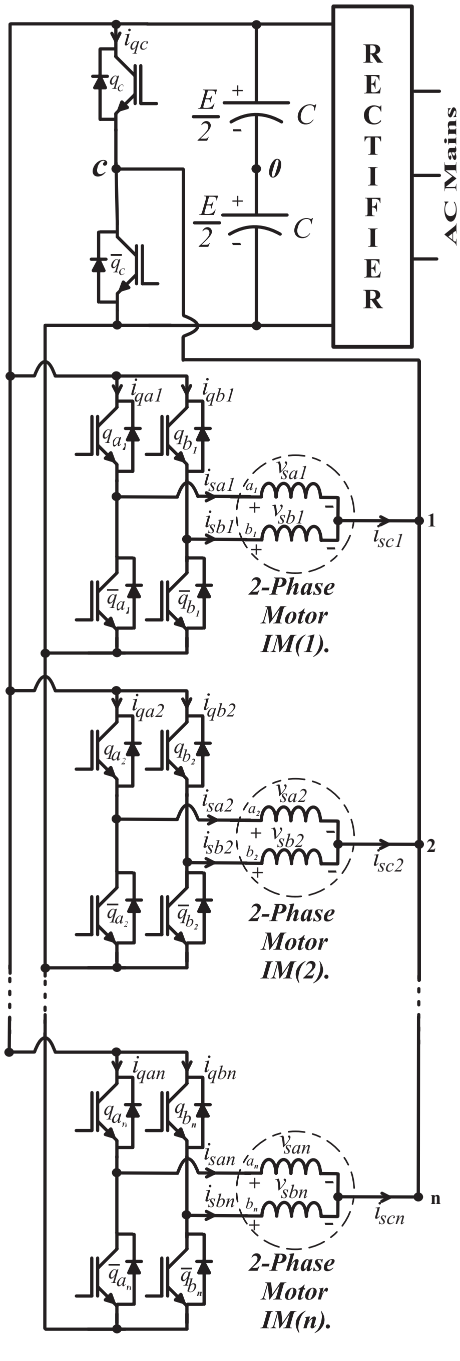

Figura 1 Two-phase multi-machine drive system for configuration A.

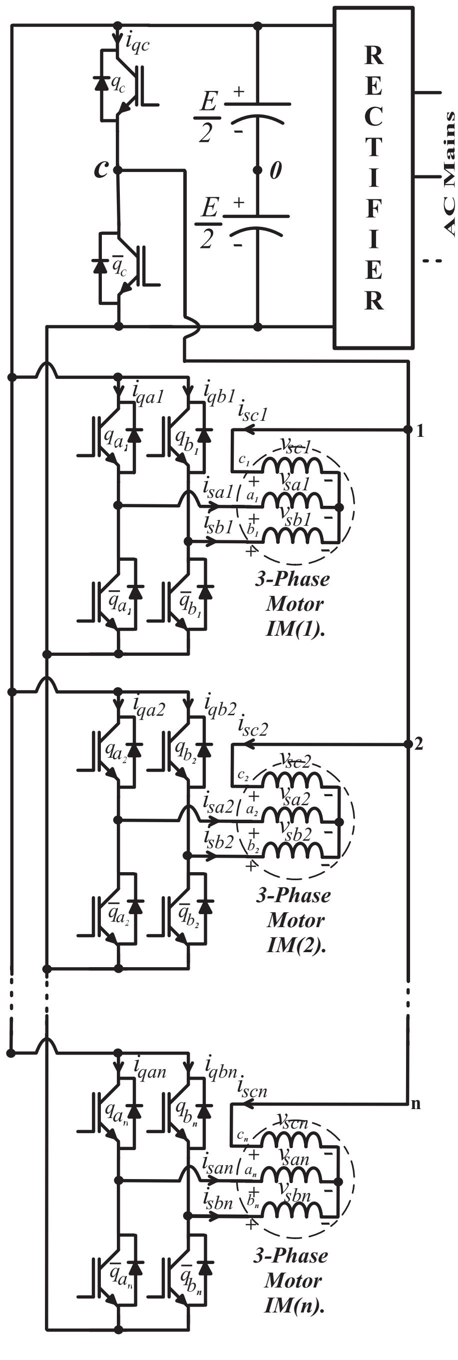

Figura 2 Three-phase multi-machine drive system for configuration B.

PWM modulator [7], [2]. The local apportioning factor μ_j ($0 \leq \mu_j \leq 1$) is given by

$$\mu_j = t_{oij}/t_{oj} \tag{9}$$

to split the local free-wheeling period t_o (period in which voltages v_{aj0}, v_{bj0} and v_{c0} are equal) at the beginning $[t_{oij} = \mu_j t_{oj}]$ and at the end $[t_{ofj} = (1 - \mu_j)t_{oj}]$ of the switching period [7], [2]. The apportioning factor can be changed as a function of the modulation index (m_j) to reduce the THD (total harmonic distortion) of the a j^{th} machine voltage. In this case, it is possible to control how the harmonic distortion is split between the machines.

Besides (8), the voltage $v^*_{\mu j}$ must also obey the other k^{th} (for $k = 1$ to n with $k \neq j$) machine voltages. Then, from (5) and (6) for the k^{th} machine (i.e., replacing l by k) the limits for $v^*_{\mu j}$ can be calculated as

$$v^*_{\mu j\,\max} = E/2 - \min U_k \text{ (for } k = 1 \text{ to } n,\ k \neq j) \tag{10}$$
$$v^*_{\mu j\,\min} = -E/2 - \max U_k \text{ (for } k = 1 \text{ to } n,\ k \neq j) \tag{11}$$

where $U_k = \{v^*_{sak}, v^*_{sbk}\}$.

Based on the previous discussion, the algorithm being proposed to determine the switch command signals is given below:

Step 1. Choose the local apportioning factor μ_j so that the THD of the j^{th} machine voltage is optimized and calculate $v^*_{\mu j}$ from (8).
Step 2. Determine the $v^*_{\mu j}$ limits $v^*_{\mu j\max}$ and $v^*_{\mu j\min}$ from (10) and (11). Clamp $v^*_{\mu j}$ to $v^*_{\mu j\max}$ if $v^*_{\mu j} > v^*_{\mu j\max}$ and $v^*_{\mu j}$ to $v^*_{\mu j\min}$ if $v^*_{\mu j} < v^*_{\mu j\min}$.
Step 3. Using $v^*_{\mu} = v^*_{\mu j}$ determine v^*_{al0}, v^*_{bl0}, and v^*_{c0} from (5)-(7) for all n machines.
Step 4. Finally, once the mid-point voltages have been determined, calculate pulse-widths τ_{al}, τ_{bl} and τ_c for all n machines by using

$$\tau_{al} = \frac{T}{2} + \frac{T}{E}v^*_{al0} \quad (12)$$

$$\tau_{bl} = \frac{T}{2} + \frac{T}{E}v^*_{bl0} \quad (13)$$

$$\tau_{c} = \frac{T}{2} + \frac{T}{E}v^*_{c0} \quad (14)$$

and programmable timers.

This algorithm can be also implemented by comparing the modulating reference signal v^*_{al0}, v^*_{bl0} and v^*_{c0} to a high frequency triangular carrier signal.

Method II: General apportioning factor

The PWM control can be defined using a general apportioning factor μ $(0 \leq \mu \leq 1)$ to split the general freewheeling period t_o (period in which n machine voltages v_{al0}, v_{bl0} and v_{c0} are equals) at the beginning and at the end of the switching period.

In this case voltage v^*_{μ} can be determined by taking into account the general apportioning factor μ. In this case v^*_{μ} is given by

$$v^*_{\mu} = E(\mu - \frac{1}{2}) - \mu v^*_{\max} + (\mu - 1)v^*_{\min}. \quad (15)$$

where $v^*_{\max} = \max V_l$ and $v^*_{\min} = \min V_l$, where $V_l = \{v^*_{sal}, v^*_{sbl}, 0\}$ for $l = 1$ to n.

The algorithm to determine the switch command signals is given below:
Step 1. Choose the apportioning factor μ and calculate v^*_{μ} from (15).
Step 2. Using v^*_{μ} determine v^*_{al0}, v^*_{bl0} and v^*_{c0} from (5)-(7) for all n machines.
Step 4. Finally, once the mid-point voltages have been determined, calculate pulse-widths τ_{al}, τ_{bl} and τ_c for all n machines by using (12)-(14).

IV. PWM CONTROL - CONFIGURATION B

Considering the configuration shown in Fig. 2, the machine voltages v_{sal}, v_{sbl} and v_{scl}, are expressed by

$$v_{sal} = v_{al0} - v_{n0} = (2q_{al} - 1)\frac{E}{2} - v_{n0} \quad (16)$$

$$v_{sbl} = v_{bl0} - v_{n0} = (2q_{bl} - 1)\frac{E}{2} - v_{n0} \quad (17)$$

$$v_{scl} = v_{cl0} - v_{n0} = (2q_{cl} - 1)\frac{E}{2} - v_{n0} \quad (18)$$

where E is the dc-bus voltage, v_{al0} , v_{bl0} and v_{cl0} are the machine voltages referred to the dc-bus midpoint ($'0'$) (i.e., the mid-point voltages).

If the desired machines phase voltages are given by v^*_{sal}, v^*_{sbl} and v^*_{scl}, then the voltages referred to the capacitor bank midpoint may be expressed by

$$v^*_{al0} = v^*_{sal} + v^*_{n0} \quad (19)$$

$$v^*_{bl0} = v^*_{sbl} + v^*_{n0} \quad (20)$$

$$v^*_{cl0} = v^*_{scl} + v^*_{n0} \quad (21)$$

where $v^*_{c0} = v^*_{cl0}$.

Similarly to configuration A, the PWM control for configuration B can be done in accordance with one of two methods [8].

V. SHARED-LEG CURRENTS

Configuration A

It can be shown that the average current $\bar{i}_{qc}$, in the switch q_c, is given by:

$$\bar{i}_{qc} = (\frac{v^*_{c0}}{E} + \frac{1}{2})\sum_{l=1}^{n}(\bar{i}_{sal} + \bar{i}_{sbl}). \quad (22)$$

Then, the current flowing through the switch of the shared-leg is greater than the current in the other switches. However, when $v^*_{c0} = 0$, the current $\bar{i}_{qc}$ has a factor $1/2$ that reduces the instantaneous current in steady-state operation of the drive. But the current rating is defined by the sum of the currents in the leg $(\sum_{l=1}^{n}(\bar{i}_{sal} + \bar{i}_{sbl}))$. The analysis for switch $\overline{q}_c$ is similar.

Configuration B

In this case same type of relation hold. The average current $\bar{i}_{qc}$, in the switch q_c, is given by:

$$\bar{i}_{qc} = (\frac{v^*_{c0}}{E} + \frac{1}{2})\sum_{l=1}^{n}\bar{i}_{scl}. \quad (23)$$

VI. VOLTAGE RATING

Configuration A

The amplitude of the sinusoidal voltage for all n machine is

$$V_l \leq E/\sqrt{2} \text{ for } l = 1, n \quad (24)$$

$$V_k + V_j \leq E \text{ for } k, j = 1, n \text{ with } k \neq j \quad (25)$$

where V_k and V_j are the amplitude of the sinusoidal phase voltage of the machines k and j, respectively.

Configuration B

In this case, we have

$$V_k + V_j \leq E/\sqrt{3} \text{ for } k, j = 1, n \text{ with } k \neq j \quad (26)$$

VII. COMPARISON OF THE CONFIGURATIONS

A comparison between the drive configurations is summarized in Table 1. It shows the ratings for configurations of Fig. 1 and Fig. 2 operating at the same power level. In this table, the dc-bus voltage (E) and the amplitude of the fundamental component of phase voltage (V) are normalized in relation to the phase voltage of a standard

Tabela 1 Comparison of the configurations.

	Configuration A	Configuration B
E	$\sqrt{2}$	$\sqrt{3}$
V	$\sqrt{3/2}$	1
I	$\sqrt{3/2}$	1
I_{sl}	$\sqrt{3}$	1

three-leg three-phase machine drive. The phase current (I) and the amplitude of the shared-leg current (I_{sl}) are normalized in relation to the values of a standard three-leg three-phase machine drive, whereas I_{sl} is normalized in relation to the shared leg current of the configuration B. We can see that configuration A demand the lowest dc-bus voltage, while configuration B demands the smallest current in the switches, including the switches of shared leg. However, if the criteria is the THD of the output voltage, configuration B is better than configuration A.

VIII. EXPERIMENTAL RESULTS

The topologies have been implemented experimentally in the laboratory supplying two two-phase machines, (configuration A) and two three-phase machines (configuration B). In the experimental tests the switching frequency was $10kHz$. The set-up used in the experimental tests is based on a microcomputer (PC-Pentium) equipped with appropriate plug-in boards and sensors.

Selected experimental results are shown in Fig.3 and Fig. 4. Two $1/4Hp$ two-phase motors and two $1Hp$ three-phase motors are controlled at different frequencies. Fig. 3 presents the currents i_{sa1}, i_{sb1} (machine 1) at $10Hz$ and i_{sa2}, i_{sb2} (machine 2) at $20Hz$ for configuration A. Fig.4 presents the currents i_{sa1}, $i_{sb1}$and i_{sc1} (machine 1) at $10Hz$ and i_{sa2}, i_{sb2} and i_{sc2} (machine 2) at $20Hz$ for configuration B. The behavior of the currents is fairly adequate.

IX. CONCLUSIONS

This paper has examined two component minimized multiple two and three-phase ac drive systems. Configuration A uses two-phase machines while configuration B uses three-phase machines. Both configurations use multiple two-leg inverter topologies with a same shared leg. The overall comparison of the configurations A and B favors configuration A, Fig.1, when the the lowest dc-bus voltage is the criteria. However, if current in the switches, including the switches of shared leg, and THD of the output voltage, are the criteria, the configuration B, Fig.2, is preferable.

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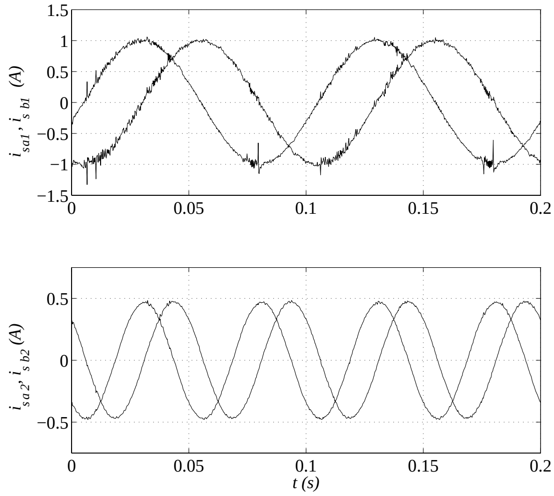

Figura 3 Currents waveforms for the configuration A supplying two machines - $10Hz$ e $20Hz$.

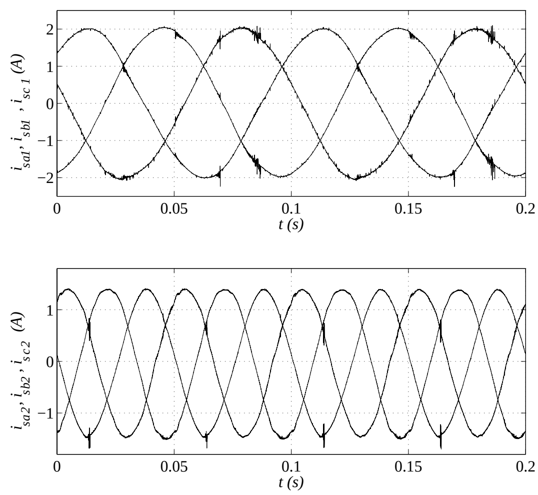

Figura 4 Currents waveforms for the configuration B supplying two machines - $10Hz$ e $20Hz$

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