Abstract— This paper presents a method for operating cascaded multilevel inverters when one or more power cells are damaged. The method is based on the use of additional switches in the power circuit to bypass the faulty cell. To control the cells, the angle of phase shifting in the carrier signals is modified according to the number of operating cells, to minimize the load voltage distortion, when the inverter operates in failure mode. The reference signals of the PWM modulators are also modified to increase the output voltage. Simulation and experimental results show the effectiveness of this method, which significantly increases the reliability of the drive.

Keywords- Fault tolerance; multilevel inverters; power electronics.

I. INTRODUCTION

Medium voltage inverters are, in general, high power equipment and when they fail they create great losses in production. For this reason, reliability is a very important issue in this family of converters. In addition, medium voltage inverters use a high number of power semiconductors and for this reason it may be considered that they are less reliable [1].

However, a different approach is to consider that medium voltage inverters offer more possibilities in the power circuit to allow for operation even during faulty conditions. This approach has recently been considered for the flying capacitor topology [2], [3], [4]. The design of a sensor to improve the short circuit tolerance of this topology is reported in [4].

This work is dedicated to a different family of medium voltage inverters, the so called cascaded multicell topology, which uses several cells in series connection to generate higher voltages [5], [6]. Each cell is supplied by an isolated three-phase secondary of the input transformer.

This paper proposes a method to increase the reliability of cascaded multicell inverters, permitting the operation even with some faulty cells. This is achieved by adding small contactors in the power circuit and modifying the modulation strategy, to maintain the generation of balanced voltages.

II. THE MEDIUM VOLTAGE INVERTER

A. Power circuit

Fig. 1 represents the power circuit of an 11-level medium voltage inverter, which has 5 cells in series connection in each phase. This inverter has 15 modules (cells). Each cell is fed by isolated three-phase voltages to generate a non-controlled dc-link, as shown in Fig. 2. The output part of the cell has a single-phase inverter which delivers three values: +VDC, 0 and −VDC, generating a voltage in the range of 0–480 VAC. Five cells in series connection are used to generate a phase voltage of 2400 VAC, which corresponds to a line voltage of 4160 VAC.

Table I shows the solutions adopted for voltages 2.3 kV to 4.16 kV.

![Figure 1. Topology of an inverter with 15 cells.](image1)

![Figure 2. Power circuit of each cell.](image2)

<table>
<thead>
<tr>
<th>Levels</th>
<th>Cells per phase</th>
<th>Output voltage (kV)</th>
<th>Pulses in input current</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>3</td>
<td>2.3</td>
<td>18</td>
</tr>
<tr>
<td>9</td>
<td>4</td>
<td>3.3</td>
<td>24</td>
</tr>
<tr>
<td>11</td>
<td>5</td>
<td>4.16</td>
<td>30</td>
</tr>
</tbody>
</table>

TABLE I. CASCADED INVERTERS USED IN MEDIUM-VOLTAGE DRIVES
B. Modulation of the inverter

The modulation of each cell is done using unipolar PWM generated by using a triangular carrier signal with a frequency of 600 [Hz], as shown in Fig. 3.

The carrier signals of the different cells in each phase are shifted in order to reduce the distortion in the load voltage [5], [6]. Another advantageous consequence of this phase-shifting technique is that the effective switching frequency of the load voltage is \(N_c\) times the switching frequency of each cell (\(N_c\) is the number of cells in series connection in each phase). This property allows for a reduction in the switching frequency of each cell, thus reducing the losses.

III. Operation Under Abnormal Conditions

A. Some reliability considerations

The main idea to improve reliability is to bypass the damaged cell by using the bypass contactor shown in Fig. 2, to allow for operation of the inverter with reduced capacity. This solution protects against the failure of all components in the power circuit of each cell, rather than just the damage of some power semiconductors.

In the following analysis it is supposed that a cascaded inverter has \(N\) modules (cells) and cannot tolerate any failure. If the probability that a power cell will function properly during a time interval is \(R\), then the probability that all \(N\) cells will function properly during the same time interval is \(R^N\). Consequently, the inverter reliability will be \(R^N\).

If the same modular drive can tolerate one failure, the drive reliability will be \(R^N - N*R^{(N-1)}*(1-R)\). It is clear that this drive has a higher reliability than one with no tolerance for failures. Similar equations can be applied to drives that can tolerate a larger number of faults. For example, if no faults can be tolerated in a 15-module drive and each cell has 99% reliability during an arbitrary time interval, then the reliability of the drive is 86%. However, if one failure can be tolerated the drive reliability increases to 99.03%, and if two failures can be tolerated the drive reliability increases to 99.9%.

B. The simple solution

When cells are bypassed in one of the drive phases, the output voltage will tend to become unbalanced. Fig. 4 shows the voltages delivered by the inverter when one faulty cell in phase A and two faulty cells in phase B have been bypassed. Due to the modulation scheme, the phase voltages have a phase displacement of 120° with different amplitudes. The simplest solution to avoid the generation of unbalanced load voltages is to additionally bypass three cells in the other two phases, generating the balanced voltages shown in Fig. 5.

The price that must be paid for this solution is that the voltage is reduced to 60%, and three operating cells are not used. To reduce the voltage distortion, the phase shifting between the carriers of the cells in each phase must be changed from \(\theta_c = 36°\) to \(\theta_c' = 60°\).

C. Maximizing the load voltage

1) Principle: The proposed method takes advantage of the fact that the star-point of the modules is floating, and is not connected to the neutral of the motor. The star-point can be shifted away from the motor neutral, and the phase angles of the module voltages can be adjusted, so that a balanced set of motor voltages is obtained even though the inverter phase voltages are not balanced.

![Figure 3](image1.png) Voltages of a cell. Upper: Reference voltages and triangular carrier. Lower: Output voltage of a cell.

![Figure 4](image2.png) The drive of Fig. 1 with 3 faulty cells bypassed.

![Figure 5](image3.png) The drive of Fig. 4 re-balanced by bypassing functional cells.
2) Calculation of the references: Fig. 6 shows the general voltage diagram when all inverter phases have a different amount of operating cells.

The problem to be solved is to find the corresponding angles $\alpha$, $\beta$, and $\gamma$ necessary to generate balanced line voltages at the load when the phase voltages of the inverter have different amplitudes. In this figure, the phase voltages $V_j$ with $j = A, B, C$, are represented by the vectors $(X_j, Y_j)$. Voltage $V_A$ is located in the real axis of the complex plane and, for this reason, its imaginary part is $Y_A = 0$.

The equivalence of line voltages magnitude is given by

$$|V_{Ac}| = |V_{Ac}|,$$  \hspace{1cm} (1)

$$|V_{Ab}| = |V_{Cb}|.$$  \hspace{1cm} (2)

These equations can be expressed in terms of the real and imaginary parts of the voltages, as follows:

$$(X_b - X_A)^2 + Y_b^2 = (X_c - X_A)^2 + Y_c^2$$

$$= (X_b - X_A)^2 + Y_b^2 = (X_c - X_A)^2 + (Y_b - Y_c)^2.$$  \hspace{1cm} (3)

In addition, the following equations are valid:

$$V_b^2 = X_b^2 + Y_b^2,$$  \hspace{1cm} (5)

$$V_c^2 = X_c^2 + Y_c^2.$$  \hspace{1cm} (6)

It is important to point out that the effective values (module) of the phase voltages $V_A$, $V_B$ and $V_C$ are known, since these values are obtained directly from the number of cells in operation.

The four nonlinear equations (3) to (6) have the four unknown variables $X_b$, $Y_b$, $X_c$ and $Y_c$. These equations are solved by using the command `solve` in the software MAPLE®.

Finally, the angles are obtained from

$$\alpha = \arctan\left(\frac{Y_b}{X_b}\right),$$  \hspace{1cm} (7)

$$\gamma = \arctan\left(\frac{Y_c}{X_c}\right),$$  \hspace{1cm} (8)

$$\beta = 360^\circ - \alpha - \gamma.$$  \hspace{1cm} (9)

Fig. 7 shows the situation of a 15-module drive (5 cells per phase) under similar conditions of Fig. 4: all five cells remain in phase A, one cell bypassed in phase B and two cells bypassed in phase C.

In the case of Fig. 7, the angles between the phase voltages of the inverter are $\alpha = 96.9^\circ$, $\beta = 150^\circ$ and $\gamma = 113.1^\circ$, generating balanced line voltages.

This solution uses all operating cells and generates a load voltage 30% higher than the simplest solution shown in Fig. 5.

The phase displacement of the reference voltages, depending on the number of faulted cells, is calculated previously, in order to reduce processing time during the operation of the inverter.

IV. RESULTS

Fig. 8 represents the operation of the 15 cells inverter under normal conditions, i.e. with no faulty cells.

Fig. 9 shows the operation of the inverter with four cells bypassed in phase A, and one cell bypassed in phase C. In this result, the reference voltages and the carrier signals maintain the same values and phase displacements of the normal operation. This condition generates unbalanced voltages and currents in the load, which is observed in the middle and lower part of Fig. 9. This condition is not acceptable for the machine.

![Figure 6. General diagram for angles calculation.](image1)

![Figure 7. The drive of Fig. 1 with faulted cells and balanced operation.](image2)
As mentioned above, the simplest solution to avoid the generation of unbalanced load voltages is to bypass four cells in phase B and three additional cells in phase C, in order to obtain the same number of cells in each phase, generating the balanced voltages shown in Fig. 10. However, the obtained balanced voltages and currents are significantly reduced with respect to the number of the total operating cells, because with this solution there is only one cell working in each phase. In addition, the load currents are reduced to 20% of the values obtained with all operating cells.

Fig. 11 represents the operation of the inverter with the same five faulty cells of Fig. 9. In this case, the neutral is shifted to generate balanced voltages at the output, which is achieved with \( \alpha = 60^\circ \) and \( \beta = 60^\circ \) (see Fig. 6) for the reference voltages. In addition, the voltages and currents in the load have higher values than those obtained in Fig. 10. In these results, the angles of the carriers were modified to minimize the distortion. More precisely, the phase shifting between the carriers of the cells in phase C is now of \( 45^\circ \) (instead of \( 36^\circ \)) and in phase A the displacement of \( 36^\circ \) is maintained. In this case the reduction of the load currents is 55% of the original values (see Fig. 8), but this situation is much better than in the case of Fig. 10.
Fig. 12 shows experimental results obtained from a 4.16 kV 15-module inverter operating with one cell bypassed in phase A, and four cells bypassed in phase B. The top signals are the reference signals to phases B and C into the PWM modulator, which contain a zero sequence component to increase the voltages delivered to the load. The bottom signals are two of the motor currents (phases B and C). It can be observed that the load currents are balanced.

A very important issue in the operation of the inverter under fault conditions with this strategy is the behavior of input current harmonics. In effect, the input transformer of the inverter is designed considering that all cells are operating. Under this condition, the phase displacement of the secondaries allows for the cancellation of current harmonics. If some cells are bypassed, the condition for the cancellation is lost, which will create an increase in the harmonics. Fig. 13 shows the input current spectrum for a 15-module drive, for the cases of 0, 1, 2 and 3 cells bypassed in one phase group.

Fig. 13 confirms the increase in the current harmonics as modules are bypassed. However, the harmonics are always under values permitted by IEEE 519 with one cell bypassed, and probably with two or three cells bypassed, depending on the source impedance.

V. COMMENTS AND CONCLUSIONS

The reliability of the inverter can be improved drastically using the method presented in this paper, by adding a few simple contactors in the power circuit. In addition, the modification of the reference voltages delivered to the modulator allows for an increase in the voltage available at the load, reaching a high utilization of the operating cells.

The operation of the inverter with bypassed cells deteriorates the quality of the input current. However, the increase in the harmonics is not excessive and can be tolerated in an emergency situation.

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REFERENCES