Lowering Harmonic Effects On Single Phase Non Regenerative Power Cells Coupled With Multi Level Inverter

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Abstract—Inter harmonics exist within the ac provide currents in ac/dc/ac drives principally as a result of the poor decoupled behavior of the dc-link stage. This issue is especially evident once totally different input/output operational frequencies are used, inflicting harmful effects on power transformers and reducing the system potency and power quality. Consequently, massive interharmonics is found in converters with single-phase stages, as they need massive electrolytic capacitors to separate the dc-link second harmonic of voltage and current, that is sometimes not absolutely accomplished. This can be the case of the cascade structure device supported single-phase power cells, wherever every module features a single-phase rectifier and a single-phase electrical converter stage that can’t be effectively decoupled with normal size capacitors. This paper shows that it’s attainable to enhance the standard of the ability cell input currents once the input/output frequencies area unit totally different within the cascade structure device. this can be achieved by suggests that of magnetic couplings among the dc-links of the ability cells that feed totally different output phases, whereas keeping the high power quality on the load aspect.

Index Terms—AC–AC power conversion, electromagnetic coupling, multi cell single-phase topology, multilevel system, power electronics, variable-speed drives.

INTRODUCTION

CONTROLLED power provides for medium voltage industrial electrical masses might cause power quality issues as a result of the presence of voltage and current harmonics created by the ability natural philosophy that management the power. The existence of currents with high harmonic content, subharmonics, and dc parts created by nonlinear masses affects the potency of the feeding electrical device by increasing the losses within the magnetic cores and windings, thus decreasing their capability to transmit power [1]–[4]. A basic resolution addressing the harmonic currents created by nonlinear masses is to filter them out with passive filters. However, once adjustable speed drives generate sub- and interharmonics, the likelihood of eliminating them with passive filters is reduced, since their frequencies rely on the converter’s output frequency and therefore the ensuing passive filter size would be impractical [4]–[6]. Since the start of the last decade, one in all the most advances in power natural philosophy was the inclusion of cascade construction converters as Associate in Nursing possibility for medium voltage drives. These converters use multipulse transformers to attain a decent power quality within the electrical grid. Similarly, this instrumentation has high power quality and responsibility indexes on the load aspect. These characteristics create this instrumentation well suited for industrial applications [7], [8]. However, energy potency of multipulse transformers employed in cascade converters is expensive, as a result of the electrolytic capacitors within the power cells find yourself very giant. this can be primarily as a result of cascade converters use power cells primarily based upon single-phase inverters that inject an outsized second current harmonic back to the dc-link, that should then be filtered out by the electrolytic capacitors [7]. it’s far-famed that a bank of capacitances (mainly a string of series connected capacitors) is a smaller amount reliable than only 1 capacitor, in addition because it is understood that the dimensions of Associate in Nursing capacittance influences its own life [9]. Thus, from the purpose of read of the responsibility, it’s continually fascinating to scale back the dc-link capacittance. however, if the dc-link capacitance style is relaxed, the second current harmonic created by the electrical converter might cause entomb subharmonics, and even worse, dc parts within the ac input currents of the ability cells. If these currents labor under the multipulse
electrical device, they’ll decrease the system potency [10]. Classic cascade construction converters use power cells that feature 3φ-input/1φ-output stages. However, a noteworthy case, which can increase the responsibility even additional, is that the one that options 1φ-input/1φ-output stages. this can be as a result of the multipulse electrical device has simply 2/3 the quantity of secondaries needed by the three-phase version, and it conjointly needs two hundredth fewer semiconductors [10]–[13]. In these converters, the single-phase rectifier has higher harmonic content within the input currents, and, if the dc capacitance isn’t giant enough, there’ll be inter- and subharmonic parts within the load and grid currents. This work shows the adverse effects that a cascade construction device feeding a load operative at a lower frequency than the grid has on the ability quality. another topology is planned that permits the adverse effects, like unsought harmonic content and huge dc capacitance sizes, to be overcome. it’s value mentioning that the answer bestowed here has been at the start planned in [12], and it’s primarily based upon the employment of magnetic couplings between the ability cells that belong to identical basic level within the device. The planned resolution in [12] only considers ideal components; thus, no any details got regarding the look of the magnetic couplings used, and solely numerical simulations were bestowed. in contrast, in this paper, some sensible aspects of style and implementation of the magnetic coupled topology square measure thought-about, wherever experimental results can leave validation of the planned resolution. it’s conjointly necessary to notice that balanced three-phase voltages and balanced masses square measure thought-about for the planned resolution during this paper, though preliminary results show a suitable performance with unbalanced ac supplies and asymmetrical masses, such conditions square measure on the far side the scope of this manuscript.

**CHARACTERISTICS OF CASCADE MULTILEVEL CONVERTERS BASED ON SINGLE-PHASE CELLS**

A cascade multilevel converter based on 1φ-input/1φ-output stages is implemented with a multipulse transformer that distributes the energy to the array of power cells through multiple secondaries with isolated grounds. Each power cell is fed from a single-phase ac voltage, which is rectified, filtered, and then converted by means of a single-phase inverter, generating an ac voltage of variable amplitude and frequency. Thus, each power cell delivers controlled power to one phase of the load side. For this reason, a multiple of three power cells are needed in the converter to feed a three-phase load—Fig. 1(a). Hence, each power cell consists of a diode bridge rectifier, a large electrolytic capacitor that acts as the dc filter, and a single phase inverter, as shown in Fig. 1(b). These inverters are connected in a series so that each output phase can reach higher voltage magnitudes than a single power cell could withstand [7]. The basic Sinusoidal Pulse Width Modulation (SPWM) technique for these converters indicates that for nc power cells connected in a series in one phase, the carriers must be shifted 180°/nc [14]. Consider as an example the case of a converter with three power cells per phase, as in Fig. 1(a); an expected voltage waveform in one of the output phases is given in Fig. 2(a), where it can be seen that the waveform clearly has seven levels. For traditional (symmetrical) cascade multilevel converters, the maximum number of levels (Lmax) that the output voltage can reach depends upon the number nc of power cells connected in series (Lmax = 2nc + 1) [7]. This also moves the switching harmonics up in the spectrum 2nc times, as seen in Fig. 2(d). The input current normally expected in a power cell, or equivalently in a transformer’s secondary, is shown in Fig. 2(b). This current is mainly characterized by odd harmonics [see Fig. 2(e)]; however, Fig. 2(c) and (f) show that the transformer’s input currents have a very low harmonic content. This is the result of the phase-shifted secondaries in the 18-pulse transformer. In this converter, the phase shift between the isolated secondaries that feed one row of cells is 120°, while the phase shift between the isolated secondaries that feed a column of cells must meet the relation φt = 60°/nc where φt is the phase shift between the secondaries of the same column, and nc is the number of power cells that feed one output phase. Following this rule, the current harmonics with the lowest order present in the transformer’s primary winding are 6nc ± 1(k = 1, 2, . . .). However, sub- and interharmonics appear in these currents when the load operates at a lower frequency than the ac mains frequency, and the dc capacitor is not large enough, as illustrated in this work. Input line-current waveforms in the power cells are of great interest because the harmonics present in these currents increase the power losses of the feeding transformer [1], [2]. An expected input line-current waveform in a power cell is shown in Fig. 2(b), where the main distortion is caused by odd harmonics 3rd, 5th, 7th, 9th, 11th, and 13th [see Fig. 2(e)]. These odd
harmonics typically appear when oversized dc capacitors are included in the power cells, which virtually eliminates the second harmonics generated by the single-phase inverter. In a practical approach, if a rigid design is not considered and the resulting dc capacitors are not large enough, the output voltages and input currents will have significant sub- and inter harmonic components, as will be shown later. This effect has been observed before in cascade multilevel converters with PWM single-phase power cells [10], where a limited solution is presented for a converter with \( n_c = 3 \) modules per phase. Clearly, the second current harmonic

Fig. 1. Multicell topology based on single-phase diode-rectifier power cells: (a) conventional arrangement, (b) standard power cell, (c) proposed arrangement with magnetically coupled power cells, and (d) power cells magnetically coupled.
pumped by the inverter defines the dc-link capacitor size in the power cells of cascade multilevel converters.

**PROBLEM OF THE DC-LINK CAPACITOR FILTERING**

To avoid the existence of interharmonics, it is necessary to filter out the current harmonics in the dc-links, which will require large dc capacitors. It is possible to obtain an expression for the design of the dc-link capacitor in the power cell considering the maximum load current as well as the minimum frequency in the output of the converter, as presented in [12]. This can be written as

\[
C = \frac{I_{h1}[\text{max}]}{8\pi f_0[\text{min}]} V_c^{1/2}
\]  

(1)

where \( I_{h1}[\text{max}] \) is the maximum output current amplitude in the converter, \( f_0[\text{min}] \) is the minimum operating frequency of the load, and \( V_{ch} \) is the amplitude of the second voltage harmonic that is allowed in the dc-link capacitor. Although the capacitor (1) is usually designed to attenuate the second voltage harmonic amplitude \( V_{ch} \) present on the dc side of the inverter, it should also prevent the second current harmonic (or other current harmonics) taken by the inverter from circulating throughout the rectifier stage. However, this second goal is difficult to accomplish without oversizing the dc capacitor. This issue is explained by considering Kirchhoff’s current law at the dc-link node

\[
i_r = i_c + i_i
\]

(2)

where \( i_r \) is the output rectifier current, \( i_c \) is the capacitor current, and \( i_i \) represents the current required by the inverter. Clearly, if the rectifier current \( i_r \) is required to be harmonics free, the capacitor current \( i_c \) must contain all the inverter components. This could be expensive because it would require

\[
I_i = I_{h0} + \sum_{m=1}^{\infty} I_{h2m} \cos(2m\omega_0 t)
\]

(3)

where \( I_{h0} \) is the dc current component and \( I_{h2m} \) is the current harmonic amplitude required by the inverter. By using superposition to find the total current in the capacitor, the expression can be written as follows:

\[
i_c = \sum_{m=1}^{\infty} \left[ I_{h2m} \cos(2m\omega_0 t) - \alpha_m I_{h2m} \cos(2m\omega_0 t) \right]
\]

(4)
where $I_{h2m}$ is the rectifier harmonic amplitude that is taken by the capacitor, and $I_{h2m}$ is the harmonic amplitude required by the inverter but not completely supplied by the capacitor. Therefore, the amplitude $I_{h2m}$ is attenuated by the factor $a_m$. Regarding this factor $a_m$, we can say that it is strongly dependent on the size of the capacitor, and its value is between 0 and 1. In fact, if the capacitor value $C → 0$, then factor $a_m → 0$, and if the capacitor value $C → ∞$ then factor $a_m → 1$.

Taking into account (2)–(4), the rectifier output current can be written as

$$i_r = I_{h0} + ∑_{m=1}^{∞} I_{h2m} \cos(2mω_s t) + (1 - α_m) I_{h2m} \cos(2mω_s t)$$

(5)

where it is important to mention that the amplitudes of the even harmonics $I_{h2m}$ and $I_{h2m}$ depend on the power and system parameters. From the last equation, it is possible to identify three kinds of current components on the dc side of the rectifier: (i) a continuous and desired component demanded by the inverter, (ii) even harmonics generated by the same rectifier output voltage, and (iii) even harmonics demanded by the inverter. It should be emphasized that these current harmonics are related to voltage harmonics, so if they are eliminated, the current harmonics will also be eliminated.

## LINE CURRENT HARMONICS INJECTED BY THE POWER CELLS

The problem of inter and subharmonics in the transformer’s secondary currents (input ac line currents of the power cells) is caused by the presence of the even harmonics $I_{h2m}$, which are part of the normal operation of the inverter and are reflected back into the output current $i_r$ as seen in (5). For a simplified analysis, considering the typical odd harmonics in the line currents, and according to [15] and [16], a single-phase diode bridge can be represented by means of a self-synchronized switching function (SF) given by

$$SF = ∑_{n=1}^{∞} k_{n-1} \sin(2n-1)ω_s t$$

(6)

where $k0, k1, \ldots, kn$ are constants that depend on the power demand and where $n > kn-1$. In these systems, the ac input line current $i_s$ of a power cell fed by a secondary of a power transformer is the result of the multiplication between the switching function and the rectifier output current: i.e.,

$$i_s ≈ SF \cdot i_r$$

(7)

where $i_s$ is the input ac line current of the power cell or the ac line current in a transformer secondary. Regarding (7), the secondary currents are composed of a fundamental component, characteristic harmonics, inter-, and subharmonics. Therefore, $I_s$ can be written as

$$I_s = SF \cdot i_r = I_{h1} + I_{h} + I_{sh}$$

(8)

### TABLE I

<table>
<thead>
<tr>
<th>$ω_s/ω_s^*$</th>
<th>$ω_{11}^*/ω_s$</th>
<th>$ω_{12}^*/ω_s$</th>
<th>$ω_{13}^*/ω_s$</th>
<th>$ω_{14}^*/ω_s$</th>
<th>$ω_{15}^*/ω_s$</th>
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<td>2.8</td>
<td>0.8</td>
<td>1.2</td>
<td>0.6</td>
<td>0.4</td>
</tr>
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<td>2.4</td>
<td>0.6</td>
<td>1.4</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>0.7</td>
<td>2.6</td>
<td>0.4</td>
<td>1.6</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>0.6*</td>
<td>2.2</td>
<td>0.2</td>
<td>1.8</td>
<td>0.6</td>
<td>1.4</td>
</tr>
</tbody>
</table>

* Output frequency ratio used for experimental results in this paper

where, $i_{hs}$ 1, $i_{hs}$, and $i_{ih}$ are the fundamental component, the characteristic harmonics, and interharmonic (including subharmonics) components, respectively. By rearranging and separating terms from (5) and (6), it is found that

$$i_{h1} = I_{h0} K_0 \sin(ω_s t)$$

(9)

Additionally, the characteristic current harmonics can be written as follows:

$$i_{h} = I_{h0} ∑_{n=1}^{∞} K_n \sin((2n-1)ω_s t) + ∑_{m=1}^{∞} ∑_{n=1}^{∞} k_{m-n-1} \frac{h_{2m}}{2} \sin(2nω_s t - h_{m-ω_s t})$$

(10)

Where

$$h_{m+n} = 2(m+n) − 1$$

(11)

$$h_{m-n} = 2(m-n) + 1$$

(12)

while the interharmonics currents are

$$i_{sh} = ∑_{n=1}^{∞} ∑_{m=1}^{∞} k_{m-n} \frac{h_{2m}}{2} \sin(ω_{mn} t + ω_{mn} t) + \sin(ω_{mn} t + ω_{mn} t)$$

(13)

$$ω_{mn}^+ = (2n-1)ω_s + 2mω_0$$

(14)

$$ω_{mn}^- = (2n-1)ω_s − 2mω_0$$

(15)

The previous expressions confirm the presence of the 3rd, 5th, and 7th harmonic components in the secondary currents, and that the inter- and subharmonics frequencies depend upon the output frequency. This is also seen in Table I, which is consistent with the experimental data observed in Fig. 9(f).

## ELIMINATION OF NONCHARACTERISTIC HARMONICS USING INTERCELL MAGNETIC COUPLINGS

In the absence of even-harmonics required by the inverter, the output of the rectifier would have an expected harmonic profile, similar to the one shown
in Fig. 2, at least for the line currents. A solution that allows a relaxed design of the capacitor $C$, while eliminating the unwanted even current harmonics in the cells of the converter, is the use of inter cell magnetic couplings [17]. Magnetic couplings have also been used in cascade multilevel converters in order to isolate the output voltages of the power cells in case they are not isolated by a multipulse transformer [18]–[20]. The magnetic couplings proposed in this paper are devised to specifically eliminate harmonics in the dc-link, and they can be designed for low voltage and high currents. They do interact with phase-shifted voltage harmonics in the different dc-links to cancel out the current harmonics. The loop voltage equations in the topology shown in Fig. 1(d) are the following:

$$
\begin{align*}
\nu_r^c + \nu_{31} &= \nu_r^u + \nu_{12} \\
\nu_r^u + \nu_{12} &= \nu_r^u + \nu_{23} \\
\nu_r^w + \nu_{23} &= \nu_r^w + \nu_{31}
\end{align*}
$$

(16)

(17)

(18)

where $\nu_{uvr}$, $\nu_v$, and $\nu_{vw}$ are the instantaneous unfiltered voltages of each rectifier, while $\nu_{uvw}$, $\nu_{vw}$, and $\nu_{vw}$ are the instantaneous voltages present on the capacitors. These voltages excite the harmonic currents on the dc-links, so if these voltages are eliminated, or if the harmonic voltages are phase-shifted such that their summation is zero, then, it is possible to eliminate the current harmonics. From the coupled system model presented in (16)–(18), it can be found that any loop in Fig. 1(d) satisfies the expression below

$$
\frac{1}{3}([\nu_r^u + \nu_v^u + \nu_w^u] - [\nu_r^c + \nu_v^c + \nu_w^c]) = 0
$$

(19)

Because the harmonic components of $\nu_{uvr}$, $\nu_v$, and $\nu_{vw}$ are phase-shifted 120° to each other, they cancel out their action on the dc-link, suppressing the currents for these harmonics. The same happens with $\nu_{uvw}$, $\nu_{vw}$, and $\nu_{vw}$. Note that if the three power cells of Fig. 1(d) are supplied from single-phase voltages with 120° phase-shifted and positive sequences, the second harmonic will have negative sequence, while the fourth harmonic will again have positive sequence. The sixth harmonic in the dc-links will have zero sequence, so the sixth current harmonic is not canceled by the proposed magnetic arrangement. A generalization of this issue can be explained considering a new common unfiltered output voltage of rectifiers $\nu_{vr}$ [Fig. 1(d)] composed of the different instantaneous unfiltered output voltages, obtained from (19), that feed each capacitor in the coupled system as depicted below

$$
\nu_{vr}^c = \frac{1}{3} (\nu_{vr}^u + \nu_{vr}^v + \nu_{vr}^w)
$$

(20)

where each instantaneous unfiltered output voltage of rectifiers are written conveniently as

$$
\begin{align*}
\nu_{vr}^u &= \sum_{m=0}^{\infty} \nu_{hr}^{2m} \sin(2m\omega_s) \\
\nu_{vr}^v &= \sum_{m=0}^{\infty} \nu_{hr}^{2m} \sin(2m\omega_s - \frac{2m\pi}{3}) \\
\nu_{vr}^w &= \sum_{m=0}^{\infty} \nu_{hr}^{2m} \sin(2m\omega_s + \frac{2m\pi}{3})
\end{align*}
$$

(21)

(22)

(23)

Fig. 3. Key dc-link waveforms comparison between the conventional and the proposed power cells: (a) unfiltered voltage in a conventional rectifier output, (b) dc-link capacitor voltage in a power-cell of conventional topology, (c) new common unfiltered output voltage rectifier of the proposed topology, (d) dc-link capacitor voltage in a power-cell of the proposed topology, (e) output current of a conventional rectifier, (f) output current rectifier of the proposed topology, (g) voltage of the upper magnetic coupling in a dc-link, and (h) voltage of the lower magnetic coupling in a dc-link, where $Vh2m_r$ is the amplitude of even harmonics of the unfiltered output voltages of each rectifier. If these voltages are replaced in (20), it is possible to find that the new common unfiltered output voltage $\nu_{vr}^*$ can be written as

$$
\nu_{vr}^* = \sum_{m=0}^{\infty} \nu_{hr}^{6m} \sin(6m\omega_s)
$$

(24)

which means that this output voltage has only zero-sequence even harmonics, eliminating harmonics with positive or negative sequence, such as the second and fourth harmonics. A potential drawback, as a direct consequence of (24), is that the dc-link voltage in each proposed power cell is decreased compared to the dc voltage of a standard power cell. This occurs because the elimination of the second harmonic voltage, reflected in $\nu_{vr}^*$, also removes the maximum value of the voltage provided by this harmonic into the capacitors. This means that the output voltage in the coupled system is 1/3 times lower than the maximum output voltage in a system without magnetic couplings, which can be seen and compared in Fig. 3(a)–(d). The simplest solution to this problem is to increase the turn ratio of the power transformer of the proposed topology 1.5 times.
Another important issue is the peak value of the output current reached (for the same power) in both kinds of rectifiers presented in this paper. The magnetic couplings in the proposed system can transform three two-pulse rectifiers in three six-pulse rectifiers from the point of view of input currents. This means that the energy in the proposed system has a better distribution in the output of rectifiers over time, and the peak values of the currents are significantly lower than a simple two-pulse rectifier [compare Fig. 3(e) and (f)].

**KEY DESIGN GUIDELINES FOR DC MAGNETIC COUPLINGS**

**A. Size and Number of Turns in the Magnetic Couplings**

If magnetic couplings are placed in the dc-links of the power cells, an important issue that must be considered is that the dc currents could saturate the cores of these kinds of transformers. In order to prevent saturation from continuous flux in the magnetic cores, the windings and directions of the dc currents should be arranged to achieve rejection of the dc flux inside the core. This rejection does not mean the complete cancellation of the dc flux inside the cores, but rather it means a considerable reduction of the continuous component fluxes. This will allow the ac fluxes (harmonics) to be properly reflected in both windings of the magnetic couplings. There is a proper and an improper way to wind the magnetic couplings. Both approaches can be visualized using a finite element analysis depicted in Fig. 4. The incorrect way takes the core and winds it on two different regions (primary and secondary coils). This method can reject the dc flux in the core region where coils are not present, but it can easily cause saturation in the regions near the windings, as seen in Fig. 4(a). The right way to wind the couplings is by placing both primary and secondary coils in the same branch (one coil above the other) with their magnetomotive forces opposing. Thus, according to the finite element analysis, the proposed winding reduces the continuous flux into the coil region by 90% or more, compared with the previous method, as illustrated in Fig. 4(b). Even if there could be a small amount of dc flux in the cores, it is important to point out that dc fluxes do not cause power losses inside the cores [21]. In fact, dc losses will occur mainly due to the joule effect in the winding resistance of the couplings. Hence, it is necessary to consider a minimum number of turns in the couplings coils to minimize the dc losses. If only the rectifier output voltage and its second harmonic are considered in the power cell, the number of turns in the magnetic couplings can be found through the Faraday law as

$$N_r = \frac{V_{h2}}{8\pi f_s B_{\text{max}} A_c}$$  \hspace{1cm} (25)

where $N_r$ is the number of turns in the coils of the magnetic couplings, considering the rectifier just as an ac source in the dc-link; $V_{h2}$ is the amplitude of the second harmonic voltage injected by the single-phase rectifier; $f_s$ is the ac mains frequency; $A_c$ is the core cross-sectional area in the coupling; and $B_{\text{max}}$ is the saturation flux density of the material. Similarly, if only the variation of the capacitor voltage, produced by the second harmonic on the inverter side, is considered as an ac source in the dc-link, the number of turns in the magnetic couplings is

$$N_i = \frac{V_{h2}}{8\pi f_s [\text{min}] B_{\text{max}} A_c}$$  \hspace{1cm} (26)

where $N_i$ is the number of turns of the magnetic couplings considering only the inverter side as an ac source in the dc-link; $V_{h2}$ is the amplitude of the second voltage harmonic in the

![Fig. 4. Finite element analysis of two different ways for coiling magnetic couplings: (a) improper way to wind the magnetic couplings, (b) proper way to wind the magnetic couplings.](image)
B. Insulation Voltage at the Magnetic Couplings

In order to prevent insulation failures at the magnetic couplings, it is necessary to determine their minimum insulation voltage. When an analysis at three magnetically coupled power cells, as seen in Fig. 1(d), is performed, one can realize that if an instantaneous input voltage is zero in any power cell, a minimum for the new common unfiltered output voltage rectifier $v_r^*$ is produced, Fig. 3, which can be written as

$$v_r^* = \frac{1}{\sqrt{3}} V_{s \text{ max}} \quad (28)$$

where $V_{s \text{ max}}$ corresponds to the peak voltage delivered from a secondary winding of the multipulse transformer. Since the instantaneous input voltage to the power cell is zero, the minimum voltage in the dc-link capacitor, seen in (28), is supplied through the magnetic couplings in the power cell. In that same instant, the maximum amplitude voltage of both magnetic couplings in the power cells are equal, Fig. 3(g) and (h), so it is possible to find, by considering Kirchhoff’s voltage law at the dc-link, that the maximum voltage in a magnetic coupling is

$$V_{m.c \text{ max}} = \frac{V_{s \text{ max}}}{2\sqrt{3}} \quad (29)$$

where $V_{m.c \text{ max}}$ is the peak voltage in the magnetic couplings, Fig. 3. This voltage must be considered as the minimum insulation requirement. Since the maximum voltage at the load also depends on the maximum voltage in the dc-link capacitor, then, the maximum amplitude of a phase load voltage ($V_{\text{Load ph}}$) can be written as

$$V_{\text{Load ph}} = n_c \frac{2}{3} V_{s \text{ max}} \quad (30)$$

where $n_c$ is the number of power cells connected in series. From (29) and (30), it is possible to express the maximum voltage of the couplings depending on the maximum amplitude of the phase voltage at the load ($V_{\text{Load ph}}$) as follows:

$$V_{m.c \text{ max}} = \frac{\sqrt{3}}{4n_c} V_{\text{Load ph}} \quad (31)$$

Considering the line-to-line maximum voltage amplitude of the load ($V_{\text{Load}}$), we can rewrite the above expression as

$$V_{m.c \text{ max}} = \frac{1}{4n_c} V_{\text{Load}} \quad (32)$$

This is the minimum value of insulation that should be considered in the couplings, which is low compared with the load voltage. Because the maximum voltage on the dc-link is $V_{s \text{ max}}$, this must be considered as the upper bound for the insulation, which is still low compared to the load voltage.

**BRIEF COMMENT ABOUT RELIABILITY AND MODULARITY**

The use of single-phase power cells (1Φ-input/1Φ-output) in a cascaded multilevel converter can be justified also by an increased reliability of each module of the converter. It is possible to prove that the Mean Time Between Failures (MT BF) of a single-phase power cell is greater than the MT BF of a classic three-phase power cell (3Φ-input/1Φ-output) because it has a lesser number of components. It is important to remark that, regardless of the individual reliability of a power cell, what makes the cascaded multilevel converter
to be so reliable is its ability to work with a failure in one or more power cells. This is closely related to the modularity of the converter. The strategy to follow for this converter when a power cell fails is the same considered for classic cascaded multilevel converters [22], which consists in bypassing the damaged power cell and replacing it. Thus, before the change of the failed module there will be (i) a decreased power available in the load, (ii) a decreased quality of the input current to each cell as well as, (iii) a load voltage with a higher distortion. In this same regards, one point against the proposal could be the modularity. However, a good spatial design of the equipment will maintain the full system modularity. In fact, just more connecting points will be needed if the magnetic couplings are considered as a group of accessories separated of the power cells or if the magnetic couplings are included on each one.

**EXPERIMENTAL RESULTS**

The multicell topologies shown in Fig. 1 have been implemented to validate the theoretical approach. A labeled photograph of the experimental setup is shown in Fig. 6, where it is possible to see the multipulse transformer, Fig. 7(a), the power cells that include 2.2 mF dc-link capacitors, Fig. 7(b), the alternative 22 mF dc-link capacitors, Fig. 7(c), the magnetic couplings, Fig. 7(d), and the DSP and data acquisition system, Fig. 7(e)–(f).
compared in Table II), where the THD reaches up to 81.3% in the distortion, as shown in Fig. 8(b)–(c) and (f)–(g), where the THD reaches up to 81.3% in the transformer secondary and up to 16.1% in the primary currents. Size reduction of capacitors (2.2 mF) produces 12.12 [J] of energy stored in the dc capacitor. The cell input current shows an interesting 6-pulse waveform, Fig. 10(b), (f)–(g), because the sixth current harmonic remains in the dc-link. From Fig.10(g) and (h), it can be seen that the proposed solution fully eliminates current subharmonics and only the characteristic harmonics are present. This approach achieves even better cell-input currents and primary currents than the original approach that uses a larger 22 mF capacitor (THD of 56% and 5.7%, respectively)—compared in Table II, because low frequency interharmonics are not present in this case. The stored energy increases slightly (from 12.12 [J] to 12.14 [J] as compared to the Test 2), only due to the leakage inductance of each coupling. The winding arrangement of the couplings, Fig. 4, does not allow storing energy in the magnetizing inductance. The low failure rate of a magnetic coupling makes the \( MT\ BF\) of this last power cell to be just a bit reduced as compared with the power cell of Test 2 (from 46 490 to 45 977 h/failure). This inter- and subharmonics elimination method has been recently proposed [23] for a classic cascaded multilevel converter (based on 3\( \phi\)-input/1\( \phi\)-output power cells), where experimental results were obtained for similar conditions to the ones considered in this work. This allows comparing the power quality of both topologies.

CONCLUSION

Magnetic couplings among power cells in cascade structure converters supported single-phase power cells considerably cut back even harmonics within the output current of the rectifiers, reducing sub- or interharmonics. It's a tiny low modification within the power topology, one that is simple to implement and provides higher overall performance. Massive capacitors within the dc-links (22 MF = one p.u.) square measure necessary for a three kilowatt device epitome once low frequency masses (30 Hz = zero.6 p.u.) should be fed. If these massive capacitors don't seem to be thought-about within the style, there'll be sub- and inter harmonics in the output voltage and within the primary and secondary currents of the multipulse electrical device. this will be important.
once fairly dimensioned capacitors square measure employed in the dc filter, e.g., 2.2 mF = 0.1 p.u.. This additional compact size virtually fully reduces the high power quality indexes. The employment of magnetic couplings between power cells permits dc capacitors to be reduced in size during this reasonably device. In fact, they effectively eliminate even current harmonics on the load aspect and that they conjointly eliminate even harmonics from the rectifier aspect, and so sub- and interharmonics square measure suppressed in the ac input currents. The planned answer permits ac mains provide currents to be obtained with less harmonic content, that is even higher than when there square measure outsized capacitors within the power cells of the device (as shown in Table II). the whole harmonic distortion within the secondary currents are often even lower with the device at full load. The low percentages of harmonics with regard to the elemental current (less than 2%) within the primary of the electrical device will facilitate shortly the IEEE519-1992, G4/5 standards at medium-voltage and therefore the IEC 61000-3-2 standards within the PCC higher results would be obtained if the leak inductance of the multipulse electrical device were multiplied, guaranteeing the absence of sub- and interharmonics caused by the facility cell.

REFERENCES

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