A New Proposal for DFIG Grid-Side Converter as Double-Tuned Hybrid Filter to Improve the Power Quality

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***Abstract*—This paper proposes a new topology for wind turbine system based on doubly-fed induction generator (DFIG). The DFIG grid-side converter in that application will operate together with a double-tuned passive filter. The combination of the classical grid-side converter plus the double-tuned passive filter will result in the double-tuned hybrid filter. The passive filter will be tuned to eliminate two harmonic frequencies, 3th and 5th-order harmonics. While the active filter will compensate the rest of harmonics present in the load current. A detailed mathematical model about both systems: doubly-fed induction generator and the double-tuned passive filter is shown in that work, and simulation results are presented in order to prove the proposal presented.**

I. INTRODUCTION

The production of electricity from wind generators are becoming increasingly popular. In 2010, over 10% of Europe's electricity came from wind generators [1]. The wind energy industry in Europe aims to reach 180GW by 2020 and 300GW by the end of 2030. The wind generators are characterized by being sources of renewable energy and clean. In countries like Denmark, Germany and Spain, where wind power already represents a respectable slice of the total electricity produced, grid codes (GC) are increasingly demanding [2]. In this international scenario of focus on wind energy, the wind turbines based in a Doubly-Fed Induction Generator (WT-DFIG) became very popular [3]. The widespread use of wind turbines based on DFIG added to the presence of nonlinear load in the power system lead to a new concern: the current and voltage harmonics generated. This can be corrected through active power filter or hybrid power filter [4]. However there is another way from WT-DFIG which is not very common. In this kind of application one converter of the own back-to-back converter is used as an active power filter. There are only few article addressing this theme. In [3] the authors proposed a new control strategy for the Grid-Side Converter (GSC) to aim it to work as an active filter. The authors in [5] presented some studies on the feasibility of using the GSC of a DFIG-based WECS as shunt active filter for power quality enhancement by providing grid support under unbalanced load conditions. In [6] the authors studied the active filtering capability of a DFIG on a new high selective harmonic current isolation. The harmonic current loops were added to the Rotor-Side Converter (RSC) control and the harmonics current compensation was injected into a grid at the connection point to cancel the harmonics arising from the nonlinear load. In the work [7] the authors studied harmonic current mitigation ability from the GSC. A nonlinear load was connected to PCC and the active filter compensated the current of the nonlinear load, and the current drawn from the grid became quasi-sinusoidal.

The current work uses the classical control strategy for the RSC and proposes a new application for the GSC to work as hybrid filter. Thus, the GSC will operate together with a double-tuned passive filter (DTPF). The combination of the classical grid-side converter plus the double-tuned passive filter will result in the double-tuned hybrid filter (DTHF). The passive filter is tuned to two harmonic frequencies and the active filter can be compensates any harmonic currents. By the way, the proposed topology for the wind turbine will improve the quality of energy delivered to the grid. Simulation results was obtained by using PSCAD/EMTDC model and they will be presented in order to comprove the idea behind this work.

II. DFIG MODEL

Wind turbines based on doubly-fed induction generator are variable-speed wind generators. It means that there is a AC-DC-AC converter connected into the rotor windings to control the stator active and reactive power according to wind speed. The standard configuration of this generation system is shown in Fig. 1.

In that topology the stator is directly connected to the grid while the rotor winding is connected via slip rings to a converter called back-to-back. The back-to-back converter consists of two converters in a AC-DC-AC configuration, i.e, RSC and GSC. A dc-capacitor is placed between the two converters as energy storage, in order to keep the voltage variations (or ripple) in the dc-link voltage small [9]. It is possible to control the torque or the speed of the machine by the RSC. The DFIG is nowadays very popular for variable-speed wind farmers. This is mainly due to the fact of the back-to-back converter must handle only a fraction (20 to 30%) of the total power processed by machine. The equations that

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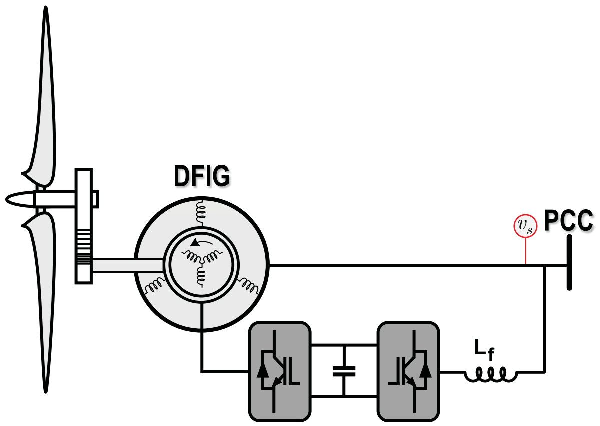

Fig. 1. Classical DFIG block diagram.

describe the voltage and the magnetic flux on the stator in a fifth-order DFIG model using a synchronous dq reference frame and space vector technique are showed bellow.

$$
\begin{aligned}
v_{sd} &= R_s i_{sd} + \frac{d\psi_{sd}}{dt} - \omega_s \psi_{sq}, \\
v_{sq} &= R_s i_{sq} + \frac{d\psi_{sq}}{dt} + \omega_s \psi_{sd}, \\
\psi_{sd} &= L_s i_{sd} + L_m i_{rd}, \\
\psi_{sq} &= L_s i_{sq} + L_m i_{rq}.
\end{aligned} \tag{1}
$$

At the same way the equations which describe the voltage and the magnetic flux on the rotor are

$$
\begin{aligned}
v_{rd} &= R_r i_{rd} + \frac{d\psi_{rd}}{dt} - (\omega_s - \omega_r)\psi_{rq}, \\
v_{rq} &= R_r i_{rq} + \frac{d\psi_{rq}}{dt} + (\omega_s - \omega_r)\psi_{rd}, \\
\psi_{rd} &= L_r i_{rd} + L_m i_{sd}, \\
\psi_{rq} &= L_r i_{rq} + L_m i_{rq}.
\end{aligned} \tag{2}
$$

Where ψ_s and ψ_r are the stator and rotor magnetic flux; L_s, L_r and L_m are the stator, rotor and magnetizing inductances; v_s and i_s are the stator voltages and currents; v_r and i_r are the rotor voltages and currents; R_r and R_s are the rotor and stator resistances; ω_s and ω_r are the synchronous and rotating angular frequencies, respectively.

From combining of the previous equations leads to the electromagnetic torque as following:

$$
\tau_e = \frac{3}{2} p (\psi_{sq} i_{sd} - \psi_{sd} i_{sq}). \tag{3}
$$

Being p the number of pairs of poles in the machine.

The system dynamics, neglecting the friction loss, is given by (4):

$$
J \frac{d\omega_r}{dt} + B\omega_r = \tau_{mec} - \tau_e. \tag{4}
$$

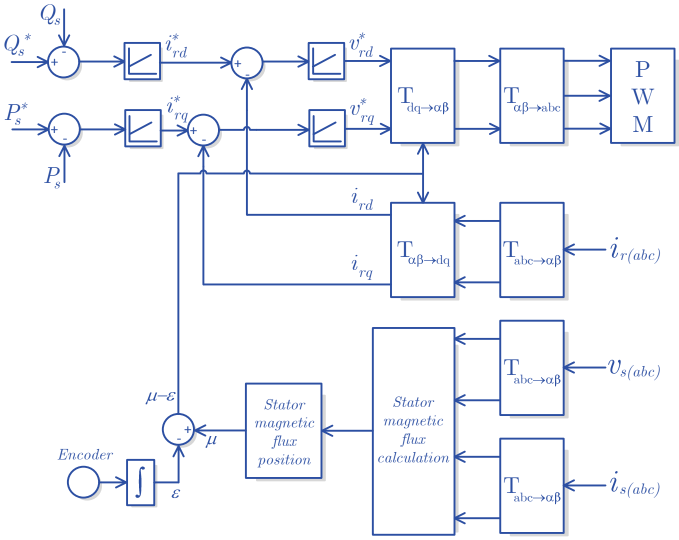

Fig. 2. Classical control block diagram to the rotor-side converter.

This last equation, together with (1) - (2) constitute the fifth order model of the DFIG that will be used in this paper.

Stator active and reactive power equations can be written as:

$$
\begin{aligned}
p_s &= v_{sd} i_{sd} + v_{sq} i_{sq}, \\
q_s &= v_{sd} i_{sq} - v_{sq} i_{sd}.
\end{aligned} \tag{5}
$$

A. The Control for the DFIG-RSC

The RSC controls the stator active and the reactive power of the machine. In this work the RSC controller was implemented considering a field-oriented control (FOC) using dq synchronous reference frame, as used in [3]. Neglecting the winding stator resistance and assuming that the stator leakage inductance is low, and still the magnetic circuit of the machine is linear, it is possible to simplify the 5 th-order model, according to [10].

Due to the low resistance of the stator winding the stator voltage ($\vec{v}_s$) can be considered ninety degrees in advanced from the stator magnetic flux ($\vec{\psi}_s$). In the used dq reference frame the stator magnetic flux is aligned to the d-axis. Then $\psi_{sd} = \left|\vec{\psi}_s\right|$ and $v_{sd} \cong 0$. The stator active and reactive power can be written as

$$
p_s = -\frac{L_m}{L_s} v_{sq} i_{rq}, \tag{6}
$$

and

$$
q_s = -\frac{L_m}{L_s} \left(\frac{v_{sq}^2}{\omega_s L_m} - v_{sq} i_{rd} \right). \tag{7}
$$

Note that the quadrature-axis rotor current i_{rq} can control the stator active power, p_s, while the direct-axis rotor current i_{rd} can be used to control the stator reactive power, q_s. The block diagram of the control strategy for the RSC is shown

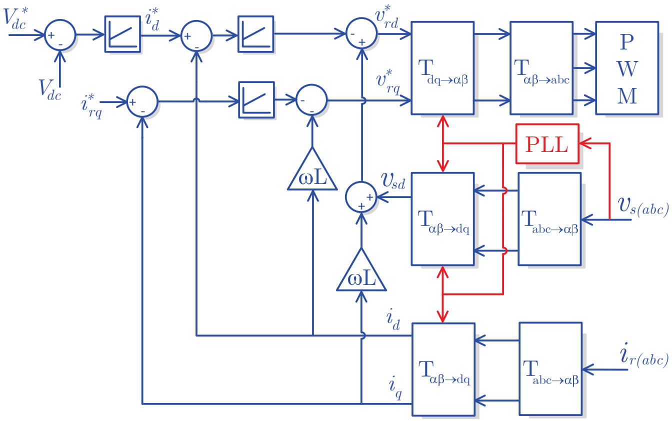

Fig. 3. A possibility to the grid-side converter control.

in Fig. 2. This control provides the decoupling of stator active and reactive power.

B. The Classical Control for the DFIG-GSC

The GSC is connected to the grid by a transformer. The main goal of this converter is to keep the dc-link voltage at the desired value regardless of the magnitude and direction of the slip power [11]. Using a synchronous dq reference frame and setting the grid voltage vector to stay aligned with d-axis, the grid voltage can be written as $v_{sd} = |\vec{v}_s|$ and $v_{sq} = 0$. The active power is controlled by d-axis in order to provide a stable dc-link voltage. The q-axis control de reactive power generated from grid [12]. Figure 3 shows a possible block diagram to the control for the grid-side converter. Through that control it is possible to control the stator active power by d-axis current component i_d, and the stator reactive power by q-axis current component i_q.

III. PROPOSED TOPOLOGY

This work proposes a topology for the WT-DFIG in which the GSC acts as hybrid power filter. It is a three-phase three-wire hybrid active power filter and its topology is showed in Fig. 4. It was used the combination of the b-shaped one-branch and the b-shaped L-type passive filters structures to build the proposed topology [13]. The structure has a set of three inductors L_1 and a single inductor L_2 installed in neutral of the system. The inductor L_2 presents a resonant frequency for the zero sequence components [8]. The passive filter can mitigate two harmonic frequencies and the active filter can mitigate the others harmonics presented in the nonlinear load currents. In this work the passive filter was tuned to eliminate the 3 th and the 5 th harmonics, and the aim of the active filter is mitigate the 7 th, 9 th, 11 th, and the 13 th harmonics.

The capacitance C and the inductance L_1 must be dimensioned to eliminate the 5 th harmonic. So, the capacitance C and the inductance L_1 make up a L_1C passive filter tuned to fifth harmonic, and it's resonance frequency is written as

$$f_5 = \frac{1}{2\pi\sqrt{L_1C}}. \tag{8}$$

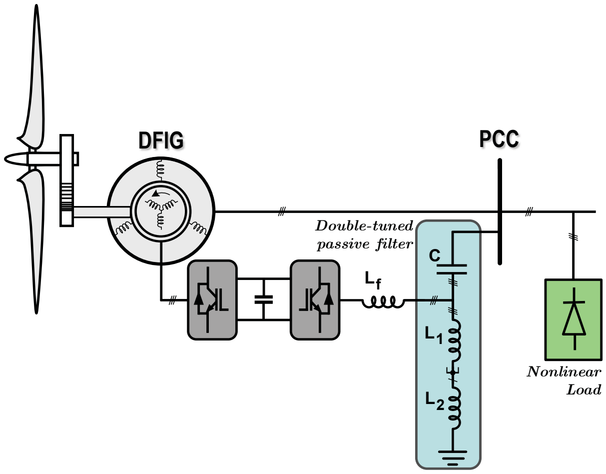

Fig. 4. Proposed Topology.

While the group composed by C, L_1 and L_2 defines another passive filter which will be tuned to third harmonic, and it's resonance frequency is given by

$$f_3 = \frac{1}{2\pi\sqrt{(L_1 + 3L_2)C}}. \tag{9}$$

The fact of the grid-side converter using a double-tuned passive filter can give the back-to-back converter many interesting features. There is a expectative about these advantages with respect to the dc-link voltage level. Because, since there is a passive branch in series with the active filter it can be possible to decrease the dc-link voltage. If that is possible really then various advantages will be inserted to the back-to-back converter in relation to the convencional topology as, for instance, the possibility to use dc-link capacitors and switches of more low cost.

1) Control Strategy for the Grid-Side Converter acts as Hybrid Filter: The purpose of the GSC control strategy is mitigate the aforementioned harmonic frequencies not filtered by the passive filter and also control the dc-link voltage of the back-to-back converter. Figure 5 shows the block diagram of the control strategy applied to the GSC in order to the converter works as active filter. Where the subscripts abc and $\alpha\beta$ mean the abc and the stationary $\alpha\beta$ coordinate systems respectively. The superscript $(*)$ and the over-bar $(-)$ mean reference and average values respectively. v_s, v_{s1}, v_{sh}, i_s, i_f, p and q are system voltage, fundamental system voltage, harmonic system voltages, stator current, compensation current, instantaneous active and imaginary power respectively. The numbers near the lines indicates the quantity of signal that enter or exit the blocks.

The control strategy is based in the instantaneous power theory. The control circuit collects the voltages of the system and changes them to a stationary orthogonal $(\alpha\beta)$ reference frame. A very powerful multiple frequency synchronization circuit called Multiple Second Order Generalized Integrator-Frequency Locked Loop (MSOGI-FLL) was used to tuning the fundamental frequency and the harmonics of the system voltage not tuned by the passive filter. The MSOGI-FLL was formally presented in [14]. It is a group of n selective and

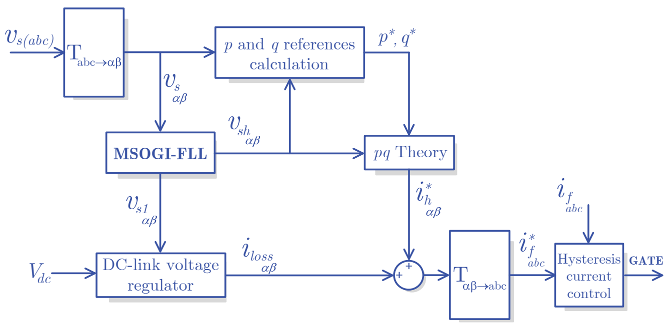

Fig. 5. Control block diagram to the proposed grid-side converter.

adaptive filters tuned at multiple desired frequencies, and it is composed by a Frequency-Locked Loop (FLL) and n Dual Second Order Generalized Integrator (DSOGI), both presented in [15].

The instantaneous active and reactive power have average and oscillating components ($p = \bar{p} + \tilde{p}$). After calculating the instantaneous power and using a low pass filter, the detection circuit separate the average power for each harmonic frequency. With the instantaneous power reference it is easy to obtain the reference compensation currents. These currents (which generate the trigger signals to the switches of the GSC) are inputs for the hysteresis control and they are computed using (10). It is worth to highlight that the dc-link regulator provides the losses components ($i_{loss\alpha\beta}$) for the compensation currents. The currents losses include the compensation for the losses in the switches of the converter. It is necessary to achieve a low ripple in dc-link voltage.

$$\begin{bmatrix} i^*_{h\alpha} \\ i^*_{h\beta} \end{bmatrix} = \frac{1}{v^2_{s\alpha} + v^2_{s\beta}} \begin{bmatrix} v_{s\alpha} & v_{s\beta} \\ v_{s\beta} & -v_{s\alpha} \end{bmatrix} \begin{bmatrix} p^*_h \\ q^*_h \end{bmatrix}. \tag{10}$$

IV. SIMULATION RESULTS

The performances of the discussed strategy have been tested considering a power system composed by the grid, a wind power generation based on doubly-fed induction generator and a nonlinear load as shown in Fig. 6. The simulation was carried out in PSCAD/EMTDC and the simulation parameters are exposed in Table I.

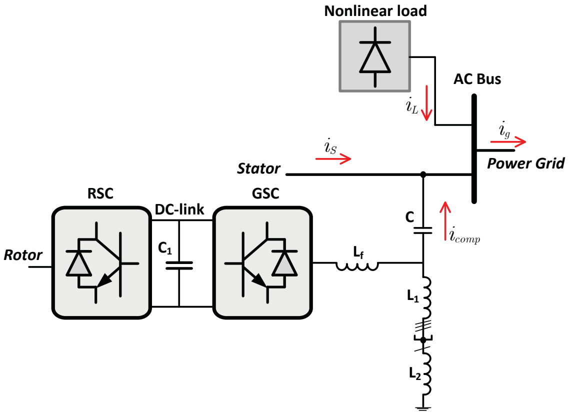

Fig. 6. Block diagram of the implemented simulation system.

Figure 7 shows the stator current. We can observe a purely sinusoidal waveform which indicates that the control system of the rotor-side converter is functioning properly.

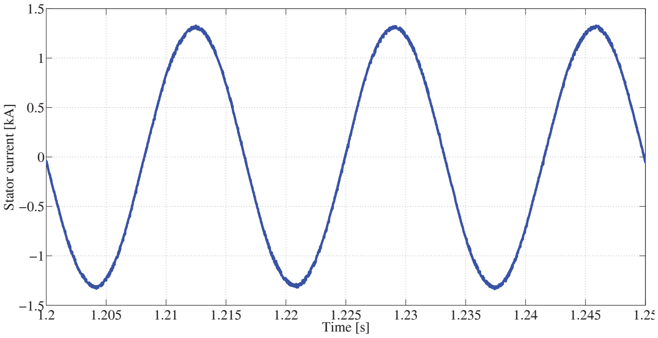

Fig. 7. Stator current in phase a.

Figures 8 and 9 show both grid and load currents for the system without and with the double-tuned hybrid filter. We can note the act of the filter on the grid current.

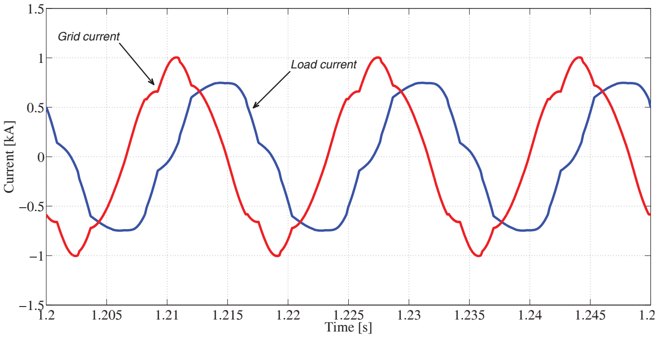

Fig. 8. Load and grid currents in phase a without hybrid active filter.

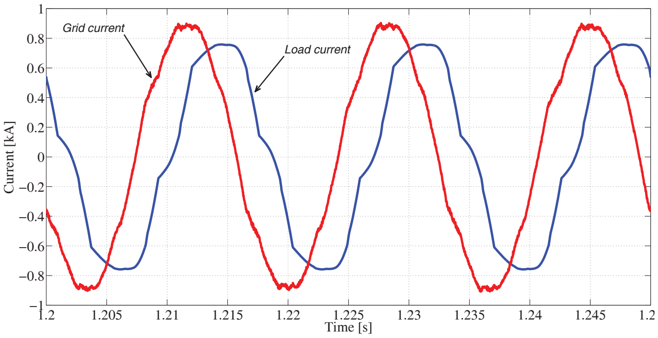

Fig. 9. Load and grid currents in phase a with hybrid active filter.

The dc-link voltage can be seen in Fig. 10. It is worth mentioning that the value of this voltage was set at 700 V.

This value is less than the one that would normally be used in a conventional WT-DFIG system. For WT-DFIG systems which use stator voltage equal to 690 V, normally, the dc-link voltage has values between 1200 and 1400 V. It means that the power switches of the back-to-back converter should be specificated to 1700 V. Thus, we can conclude that both the dc-link capacitors as the power switches will be more expensive. If it is possible decreasing the dc-link voltage and to improve

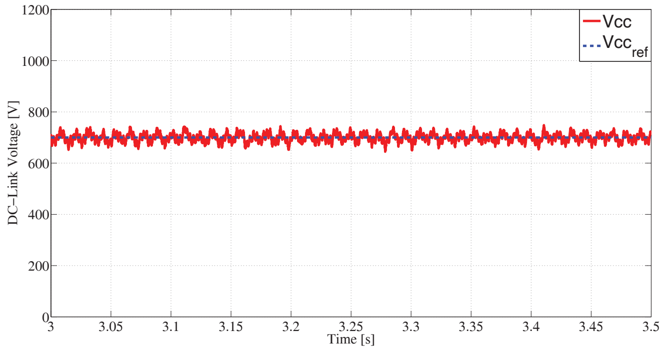

Fig. 10. DC-link voltage.

the power quality into the connection point with the grid, that is really very interesting.

Total harmonic distortions (*THD*) for load, stator and grid currents are showed in Fig. 11.

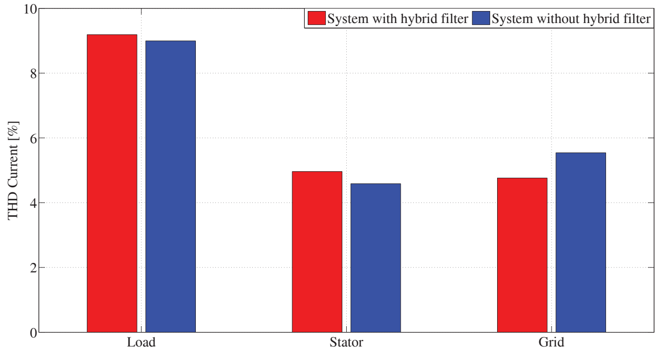

Fig. 11. Total harmonic distortions of the currents.

The reason able to explain the difference between the values of THD in grid current with and without the hybrid filter is because in both cases the DFIG's stator was connected into the grid. Thus, even when the hybrid filter was disconnected, there was injection current into grid from the DFIG's stator. So, the composition between both load and stator currents helped to decrease the grid current THD value due to the purely sinusoidal waveform of the stator current.

V. CONCLUSION

In this paper a new topology for wind turbines based on doubly-fed induction generator was proposed. The idea behind that work is use the FACTS features of the WT-DFIG to improve the power quality into the point of common coupling (PCC). Besides the inherent advantages to the active filters, through the topology proposed in this work it is possible to decrease the dc-link voltage to the levels lower than in the conventional DFIG wind turbines. This is interesting because enables the use of dc-link capacitors and power switches cheaper since they will be subjected to a smaller voltage.

The results presented in this paper, show that it is possible to control the DFIG by stable manner without changing in the classical control to the rotor-side converter. The proposed idea enables the grid-side converter compensates distorted currents from nonlinear loads since the one operates as a double-tuned hybrid filter.

TABLE I. SIMULATION PARAMETERS.

DFIG Characteristics	**Values**
Rated power	1500 kVA
Rated stator voltage	690 V
Rated rotor voltage	690 V
Rated stator frequency	60 Hz
Stator resistance	1.71 mΩ
Rotor resistance	1.92 mΩ
Stator leakage inductance	90.92 μH
Rotor leakage inductance	92.61 μH
Magnetizing inductance	3.67 mH
Angular moment of inertia (J=2H)	0.5 pu
Poles pairs	1
Double-Tuned Hybrid Filter Characteristics	**Values**
Inductance, L_1	256 μH
Inductance, L_2	152 μH
Capacitance, C	1100 μF
DC-Link Characteristics	**Values**
DC-link voltage	700 V
Capacitance, C_1	4700 μF

The kind of hybrid filter used in that work is able to eliminate two harmonic frequencies from its branch passive. Thus, the remaining harmonics can be compensated by active filter that can be selective, as used here, or not. The feature selectivity can reduce the power of the active filter.

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