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Line and Grid Impedance Impact on the Performances of a Parallel Connected Modular Inverter System

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ABSTRACT

With the rising fuel cost, increasing demand of power and the concerns for global climate change, the use of clean energy make the connection of power electronics building bloc in the heart of the current research. The high output current applications make the parallel connection of modular inverters to be a solution for the use of low power building block inverters where the output power cannot be handled by a single inverter configuration. In this context, average-modeling using average phase–leg technique allows the *n*-parallel connected inverters to be analyzed accurately and rapidly without requiring the complexity of the full switched inverter topology. The obtained analytical solution along with the equivalent circuit model makes easier the design of the control loop. The analytical solution of the *n*-parallel connected inverters shows the impact of the line and grid impedance on the performance of the overall system. The impact of this coupling has to be investigated such that the main feature of paralleling inverters is guaranteed and that the inverter mode of operation will not be compromised. The main advantage of paralleling inverters can be lost for a certain coupling impedance considerations.

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1. INTRODUCTION

In the recent years,a rapid growth in the production of electrical energy from renewable energy sources has been made. This has led to a great development in the power electronics area. Indeed, the output of each renewable energy source should be connected to a specific converter or inverter such that the converted energy will be available at the consumer level [1], [2].

In order to meet the growth of power demand of the industry, research in power electronics still needs to find solutions to the energy conversion at high power levels [3], [4]. Knowing that the conversion of electrical energy uses power electronics components,inverters based on these switches show better performances if they are used at high switching frequencies [5], with low stresses. However, the switches can withstand only limited values of current and voltage. Although, the power ratings of power semiconductor devices have increased considerably since the introduction of the first commercial switch, the maximum power ratings may be limited by technical or economical considerations. Therefore, for a higher power transfer, a degradation of efficiency with the increase of the switching frequency occurs. Unfortunately, to achieve an acceptable efficiency while increasing switching frequency, the trends enhance active research on various types of connected inverter modules such that just a fraction of the output power of the system is handled by each module. So at high level, complete power converters are developed around the power modules with either parallel or series connection.

If the system is operating in parallel, the total output power can be partitioned in a way that the overall efficiency can be kept as high as possible, then it has to be clarified at which point the number *n* of parallel inverters has to be increased in order to achieve maximum efficiency [6]. In this study, *n* identical inverters are connected in parallel both at the input and output, so that the output current and power meet higher requirements applications. This connection is made by mean of the different line impedances to the grid trough a grid impedance. This coupling along with the number *n* of inverters to be connected in parallel influence greatly on the performances of the overall circuit.

The study focuses on the development of the parallel connection of inverters which is often used to achieve power levels beyond the capacity of the high power available from a single conventional structure: such a system constitutes a special connection of building blocks to provide a highly reliable system [7], [8]. The obtained structure is capable of delivering high output current. Therefore, parallel connection of inverters has become a desirable solution, particularly in areas where a high demand for energy is required with high output current. Paralleling is used to achieve the following characteristics: redundancy, flexibility, standardization of low power components ratings, reliability, size reduction, low cost of maintenance, etc. Although the modular multilevel converters[9] offers some major advantages as to reduce the amplitude of harmonics injected into the load, the ability to work at low frenqueny with acceptable efficiency etc. but the standartisation and flexibility may be compromised.

Therefore, a comprehensive study of the global behavior of the circuit is considered. Modeling is more than necessary for a quick and methodical study of the steady and dynamic states. Several modeling techniques can then be used. The technique used in this work is theaverage phase-leg technique [11], which describes a simple averaging model to be accurately and rapidly simulated without the need for the full switched models.

Beside these advantages, parallel connection of inverters presents undesirable constraints that can be stated as current unbalance, instability due to the interaction of the different modules, circulating current between modules [10] (deterioration of the efficiency and form factor of the output currents),synchronization problem of the output currents, etc.

In this first paper,we present a modular inverter architecture in which an *n* parallel-connected inverters system is tied to an infinite grid via line and grid impedances. Because of the time varying aspect of the system, transformation in *d-q*frame is required to solve for the general solution independently of the circuit parameters. Then, a simplified average equivalent model is derived where analytical solution of different transfer functions can be analyzed whatever the number *n*of inverters is. The open loop stability for the *n*-parallel-connected inverters is analyzed with respect to the different parameters of the circuit.Finally,analytical results are given to show the effects of the coupling impedance and the number *n* of inverters to be connected in parallel on the performances of the system. Then a criterion is stated to first respect the mode of operation of the overall circuit and second to guarantee the main purpose of paralleling inverter modules.

2. PHASE-LEG ANALYSIS OF THE N PARALLEL MODULAR CONNECTED INVERTER

The average phase-leg technique is one of the essential techniques used in the analysis of switched mode power conversion [11]-[12]. It allows the switched system to be described by a simple averaging circuit model, which then enables its precise and rapid simulation without the need for full switched inverter models. Then, the inverter switches can be replaced by a function representing their average value.

The structure is composed of *n* identical parallel connected inverters at boththe input and output sides. It supplies a special load, i.e. a three phase infinite grid characterized by a grid inductance ($L_g = L_a = L_b = L_c$) and a grid resistance ($R_g = R_a = R_b = R_c$) and a maximum line to neutral voltage amplitude equal to *E*. Such a load is considered to show that, evenwith a particular case (infinite grid); the model used gives satisfactory results.The *n*-parallel inverter shares the same DC link, which can be connected to the output of a photovoltaic or wind energy system.

Each inverter is connected to the infinite grid by the means of the line impedance which is characterized by a passive first order filter ($L_{j,k}$, $R_{j,k}$), where "*j*" designs the phase line (a, b or c) and "*k*" designs the inverter number. Figure 1 shows thesystem structure of the *n*-parallel connected inverters considered in this study.

In the current-bidirectional switch based inverters, the average model of the phase leg has a voltage source in one side and a current source in the other side and where d_i is defined as the duty cycle of the top switch. The most widely applied PWM technique for the three phase voltage source inverter is the sine pulse modulation [13]. The averaging for the three-phase inverter is based on the phase-to-phase averaging in which the common mode components are intentionally neglected.

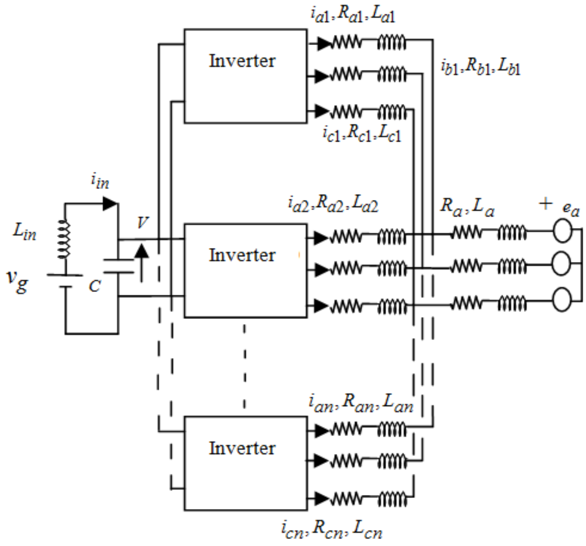

Figure 1. Circuit structure for the *n*-parallel connected inverters

Using the phase-leg technique, the electrical equations of the different phases during one switching period are given by Equation (1):

$$\left.\begin{aligned}
&L_{in}\frac{di_{in}}{dt}=v_g-V\\
&C\frac{dV}{dt}=i_{in}-\sum_{k=1}^{n}d_{3k-2}i_{ak}-\sum_{k=1}^{n}d_{3k-1}i_{bk}-\sum_{k=1}^{n}d_{3k}i_{ck}\\
&L_{ai}\frac{di_{ai}}{dt}-L_{bi}\frac{di_{bi}}{dt}=(d_{3k-2}-d_{3k-1})V\\
&-L_g\sum_{k=1}^{n}(\frac{di_{ak}}{dt}-\frac{di_{bk}}{dt})-R_g\sum_{k=1}^{n}(i_{ak}-i_{bk})-R_{ai}i_{ai}-e_a+e_b\\
&L_{bi}\frac{di_{bi}}{dt}-L_{ci}\frac{di_{ci}}{dt}=(d_{3k-1}-d_{3k})V\\
&-L_g\sum_{k=1}^{n}(\frac{di_{bk}}{dt}-\frac{di_{ck}}{dt})-R_g\sum_{k=1}^{n}(i_{bk}-i_{ck})-R_{bi}i_{bi}-e_b+e_c\\
&L_{ci}\frac{di_{ci}}{dt}-L_{ai}\frac{di_{ai}}{dt}=(d_{3k}-d_{3k-2})V\\
&-L_g\sum_{k=1}^{n}(\frac{di_{ck}}{dt}-\frac{d_{ak}}{dt})-R_g\sum_{k=1}^{n}(i_{ck}-i_{ak})-R_{ci}i_{ci}-e_c-e_a
\end{aligned}\right\} \tag{1}$$

Where:
-L_{in} and i_{ak} are respectively the input inductance and the phase line *a* current of the k^{th} inverter.
- C is the DC side capacitance.
-e_a , e_b and e_c represent the three phase line to neutral voltagesof the infinite grid.
-d_{3k-2}, d_{3k-1}, d_{3k} represent respectively the duty cycles of the phase a, b and cof the k^{th}inverter.

With sinusoidal PWM, the duty cycles are varied sinusoidally in synchronism with the ac line. The system is assumed to be perfectly balanced. The set of the above equations can be written in the state space form [14], [15] of 3*n*+2 order.

This will lead to a set of a complex nonlinear time varying averaged state space system of equations that describes the overall circuit behavior. It is necessary to make a change of coordinates to convert ac sinusoidal quantities to dc quantities prior to the average process. The reference frame in which the averaged state space exhibits a time invariant system of equations is chosen such as a multi-phase system appears as a stationary one in a coordinate rotating at the same instantaneous velocity [16]. This is done using the Park transform. For the sake of simplicity, the *n* inverters along with the line and grid impedances are considered identical such that:

$$\left.\begin{array}{l} R_{ai} = R_{bi} = R_{ci} = R_l \\ R_a = R_b = R_c = R_g \\ L_{ai} = L_{bi} = L_{ci} = L_l \\ L_a = L_b = L_c = L_g \end{array}\right\} \quad (2)$$

Doing so, the transformed set of the previous equations in the rotating *dq* coordinates can be written as follow:

$$\dot{X}_{dq} = A_{dq} X_{dq} + B_{dq} \quad (3)$$

Where the matrices A_{dq}, B_{dq} and X_{dq} have the following representation:

$$A_{dq} = \begin{bmatrix} 0 & -\frac{1}{L_{in}} & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{C} & 0 & -\frac{d_{d1}}{C} & -\frac{d_{q1}}{C} & \cdots & -\frac{d_{dn}}{C} & -\frac{d_{qn}}{C} \\ 0 & \frac{d_{d1}}{L} & -\frac{R}{L} & \omega & \cdots & 0 & \omega \\ 0 & \frac{d_{q1}}{L} & -\omega & -\frac{R}{L} & \cdots & -\omega & 0 \\ 0 & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & \frac{d_{dn}}{L} & 0 & \omega & \cdots & -\frac{R}{L} & \omega \\ 0 & \frac{d_{qn}}{L} & -\omega & 0 & \cdots & -\omega & -\frac{R}{L} \end{bmatrix} \quad (4)$$

$$B_{dq}^{t} = \begin{bmatrix} \frac{v_g}{L_{in}} & 0 & \frac{e_d}{L} & \frac{e_q}{L} & \cdots & \frac{e_d}{L} & \frac{e_q}{L} \end{bmatrix} \quad (5)$$

$$X_{dq}^{t} = \begin{bmatrix} i_{in} & V & i_{d1} & i_{q1} & \cdots & i_{dn} & i_{qn} \end{bmatrix} \quad (6)$$

Where:

$$\left.\begin{array}{l} d_{di} = \frac{\sqrt{3} d_{m_i}}{\sqrt{2}} \cos \varphi_i \\ d_{qi} = -\frac{\sqrt{3} d_{m_i}}{\sqrt{2}} \sin \varphi_i \\ R = \frac{R_l}{n} + R_g \\ L = \frac{L_l}{n} + L_g \end{array}\right\} \quad (7)$$

Where φ_i is the phase angle between the output voltage of every single inverter and the infinite grid voltage, d_{m_i} is the modulation index of the duty cyclesand, e_d and e_q are respectively the forward and backward components of the three phase infinite grid line-to-line voltage.

Referring to the matrices given in Equation (4) and (6), one can rewrite the electrical equations in the *d-q*frame. From these equations, the average circuit model of the *n*-parallel connected inverters with different parameterscanbe derived. Therefore one can obtain the average circuit model which will have the same general representation as the one derived using the average connection coefficient reflected to the DC or AC side [17]-[19]. If all the inverters are identical and have the same $d_{di} = d_d$ and $d_{qi} = d_q$, the average equivalent circuit model of Figure 3 can either be reflected to the DC side or the utility *dq* side. The fictive transformer [20] shown in Figure 3 models only the primary current and voltage from the DC to the utility side with a turn ratio of $d_d/3$ for the direct component and $d_q/3$ for the indirect component. The steady state response can be obtained in the *d-q*frame. The inverse transform can be applied to obtain the time response of any desired state.

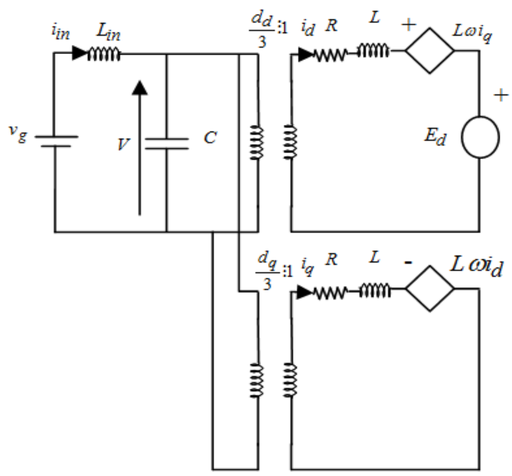

Figure 3. A simplified average equivalent circuit model

From the above circuit, one can analyze the input impedance, the different transfer functions, the output impedance seen from the DC side, etc., and then the stability analysis of the open loop circuit can be performed. From the equivalent circuit model, one can derive any transfer function that needs to be investigated.The analytical expression of the characteristic equation D_n given by:

$$D_n = CL_{in}L^2s^4 + 2CL_{in}LRs^3 + (L^2 + CL_{in}(R^2 + L^2\omega^2) + \\ 3L_{in}Ld_m^2/8)s^2 + R(2L + 3L_{in}d_m^2/8)s + 2(R^2 + L^2\omega^2) \tag{8}$$

The location of the zeros of D_n (whatever the number *n* of parallel-connected inverter is); which are functions of the parameters of the circuit, determines the stability of the overall structure.

The transfer function of the input current with respect to the input voltage and output voltage is given by:

$$i_{in}(s) = \frac{[(CL^2s^3 + 2CLRs^2 + (\frac{3}{8}Ld_m^2 + C(R^2 + L^2\omega^2))s^2 + \frac{3}{8}Rd_m^2)v_g(s) - \frac{d_m}{2\sqrt{2}}(sL\cos(\varphi) + R\cos(\varphi) + L\omega\sin(\varphi)E_d(s)}{D_n} \tag{9}$$

Note also that the position of the zeros and poles of the given transfer function depends on the parameters of the inverters which are L_{in}, R, C, d_m, L. If all the zeros of the characteristic equation are located in the left half *s*-plane, the steady state input current I_{in} and the phase output current I_a in the grid can be given by the following expressions:

$$I_{in} = \frac{3d_m^2 Rv_g/8 - 3E\sqrt{2}d_m\|Z\|\cos(\varphi - \theta)}{\|Z\|^2} \tag{10}$$

$$I_a = \frac{1}{\|Z\|}\left(\frac{d_m}{2}v_g\cos(\omega t - \frac{\pi}{6} - \varphi - \theta) - V_m\cos(\omega t - \frac{\pi}{6} - \theta)\right) \tag{11}$$

Where $\|Z\|$ and θ are respectively the magnitude and the argument of the equivalent coupling impedance defined as being equal to $R+jL\omega$.

From Equation (10) and (11), the coupling impedance plays an important role in both the transient and steady state variables of the overall circuit. This coupling impedance depends directly on the grid impedance and just a fraction of the line impedance. The above analytical equations describe the steady state input current of the *n* inverters connected in parallel whatever the value of the number *n* is. The performances of the overall circuit can then be analyzed with respect to all the transfer function parameters by means of any mathematical tool.

3. RESULTS AND INTERPRETATIONS

For a given value of $L_{in}, d_m, \varphi, v_g$ and C, the characteristic equation shows clearly that the location of zeros depends on the value of *n*,*R*and *L*. For a null coupling resistance, the four zeros are located on the imaginary axis. This contributes to an unstable system. To justify what is stated above, one can solve a numerical example as given in Table 1.

For a two-parallel connected inverters and null coupling resistance, the characteristic equation has four zeros located on the imaginary axis of the *s* domain: this makes the system unstable *(s_{12} = ± j154, 03)* and*(s_{34} = ± j407, 92)*.Therefore, for a stable open loop system, a coupling resistance has to be inserted in the circuit. The move of these zeros from the imaginary axis is more relevant for the case of the variation of the grid resistance rather than that of the line resistance.

Figure 4 shows the step response of the average input current for the case where the grid impedance is considered to be null. The base current is taken to be equal to the input current for an individual inverter with a null grid impedance: this gives a base average input current equal to 35A.

This last figure shows that an increase in the line resistance for the case of two parallel-connected inverter will induce a decrease of the steady state input current. This decrease might change completely the mode of operation of the hall structure. In this case, if the line resistance is greater than0.223Ω, the overall system works in the rectifier mode rather than the inverter mode.

Table 1. Parameters For The Analyzed Example

Input Voltage	$v_g = 400V$
Input filter	$L_{in} = 5mH; C = 5mF$
Inverter specifications	$\varphi = -\frac{\pi}{6}, d_m = 0.6, n = 2$
Line parameters	$L_l = 340\mu H, R_l = 0.1\Omega$
The infinite grid parameters	$E = 220\sqrt{2}V, L_g = 170\,\mu H, f = 50kHz$ $R_g = 0.05\Omega$

For a larger line or grid resistance, the step response of the input current shows better performances. This ensures a stable system with acceptable performances but at the detrimental of the overall circuit efficiency. The steady state input current decreases as the line or grid resistance increases (Figure 4).

The increase of the number*n* of the inverters to be connected in parallel (from 1 to 3) lets the system (see figure 5) reaches an average input current greater than the base current but at a rate which does not comply with the paralleling principle. This is mainely due to the presence of the grid impedance.

Figure 6 illustrates the effects of both the line resistance while keeping the grid resistance constant and the grid resistance while keeping the line resistance constant. First, the mode of operation of the overall circuit can be either in the inverter mode or in the rectifier mode depending on the value of the line or grid resistance. For the case (a), the inverter modeis obtained for a grid resistance smaller than 0.0617Ω while for the case (b), this same mode is obtained for a line resistance smaller than 0.1224Ω. Second, for the inverter mode, the rate of variation of the input current is greater for the case (a) rather than the case (b).

Figure 7 shows that for the inverter mode of operation, the value of the grid inductance for the case (a) has to be greater than 0.000135H meanewhile for the case (b) the line inductance has to be greater than

0.00027H. The rate of variation of the input current is greater for the case of the grid inductance variation rather than the line inductance variation.

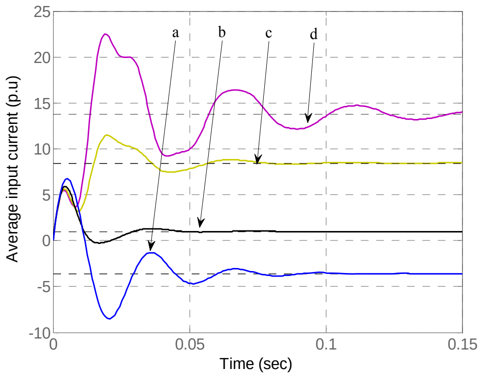

Figure 4. Step response of the average input current (p.u) for two parallel-connected inverters with null grid resistance and different values of line resistance: $a-0.5\Omega$, $b-0.2\Omega$, $c-0.1\Omega$, $d-0.05\Omega$

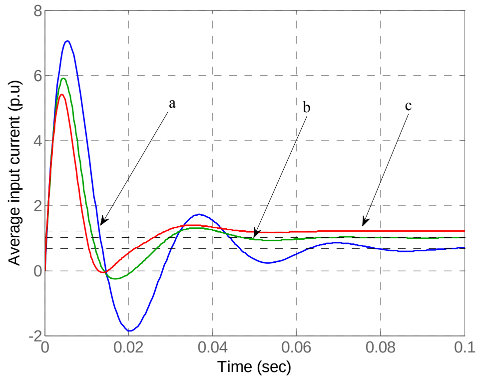

Figure 5. Step response of the input current (p.u) for a given number of parallel-connected inverters: n =1; b- n=2 and c- n=3

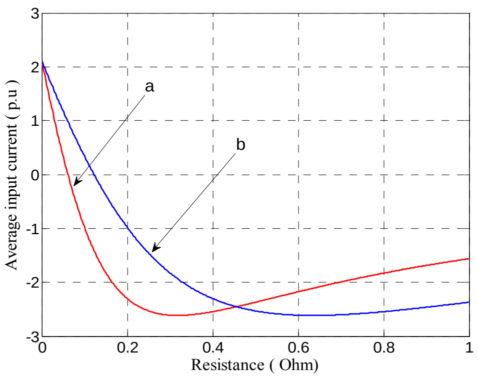

Figure 6. Line and grid resistance effects on the steady state input current (p.u): a) variation of R_g , b) variation of R_l

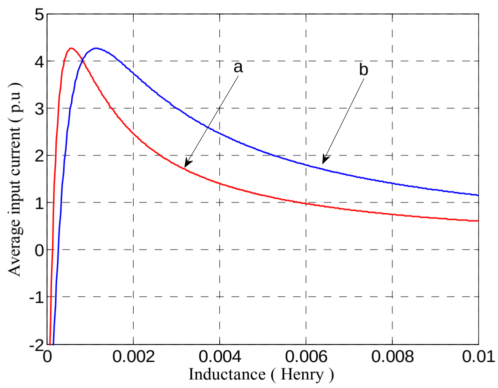

Figure 7. Line and grid inductance effects on the R_g steady state input current (p.u): a) variation of L_g , b) variation of L_l

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Figure 8 illustrates how the system can lose the main advantage of paralleling inverters: an arbitrary value of the grid impedance lets a limited increase in the input current. If the grid impedance is taken to be equal to zero, the input current with respect to the number *n* of inverters to be connected in parallel increases in a linear manner. Otherwise, this increase is nonlinear and tends to be limited as *n* increases. This is because of the reflected impedance seen fromthe DC side which increases nonlinearly with the number *n*of inverters to be connected in parallel. However, for the case (d), the increase of the reflected impedance is linear. Thus, for a maximum power transfer from the DC side to the grid, the grid impedance should be as small as possible.

For a five parallel-connected inverters, the curve (d) shows a 500%increase in the input current while the curve (a) shows only a 142% increase in it. In the case (a), the grid impedance has dramatically decreased the input power such that the five parallel-connected inverter structure is not even equivalent to a two parallel-connected inverters with null grid impedance.

This makes the choice of the coupling impedance a priority in an *n* parallel-connected inverters. Therefore, the connection port of a parallel modular structure is a key point in the design considerations.

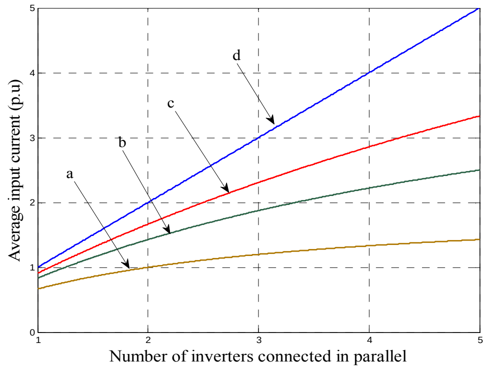

Figure 8. Average input current(p.u) with respect to thenumber n of parallel connected inverters with differentgrid impedance (R_g, L_g) :a- $0.05\,\Omega$, $0.17\,mH$;b- 0.02Ω , $0.068\,mH$; c- 0.01Ω , $0.034\,mH$ d-$0\,\Omega$, $0mH$

4. CONCLUSION

The phase leg technique applied to the *n*-parallel connected inverters gives, on one hand, a closed form solution for the 3*n*+2 order system whatever the number *n* of the inverters to be connected in parallel is. On the other hand, the obtained simplified average equivalent circuit model can be used to derive the different transfer functions of the overall circuit. This allows the analysisof the open loop system performances of the circuit with a precise determination of the poles and zeros location ofany transfer function of the system. Their position is closely linked to the value of the coupling impedance, the number *n*of inverters connected in parallel and the different parameters of the circuit. The value of the line and grid resistance plays an important role for the performances at the detrimental of the system efficiency. Furthermore, the variation of the coupling impedance that can be either affected by the line or grid impedance may completely change the mode of operation of the global circuit and then the purpose of such a circuit can be compromised.

The increase of the number *n* of the inverters to be connected in parallel may not always allow a linear increase of the average input current: this is mainly due to the equivalent coupling impedance seen by the *n* parallel inverters connected to the special load (infinite grid). However, if the grid impedance is too small compared to the line impedance, then the increase of the number of inverters to be connected in parallel tends to be close to a linear increase of the input current. This important result imposes that for a parallel-connected inverter, the connection point of the different modules should be as close as possible to the grid. This will guarantee the main advantage of paralleling inverters that is the linear increase of power as the number of inverters connected in parallel is increased; otherwise, this principle will be compromised.

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