Impact of disturbing electrical load on the renewable energy generator

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Abstract - *This paper presents a simple and straightforward method for studying the behavior of the renewable energy power sources connected to 'classical' noisy loads. It is important to study this problem because most renewable energy power plants produce direct current that needs to be inverted into ac before use. Three approaches are used. The first approach consists of modeling the system under study and then analyzing its behaviour with respect to non-linear loads. Simulations with Matlab-Simulink would then permit the visualization of the noise generation of such a highly non-linear system's behaviour; the results of these simulations are displayed in graphical form. The second approach is reducing the problem to that of designing a classical and cheap controller with fewer harmonics, compared to that of the Pulse Width Modulated (PWM) controller. Finally, the last approach consists of choosing the parameters L and C of the filter in order to avoid a resonance frequency that would coincide with the frequency of any of the harmonics.*

Résumé - *Cet article présente une méthode d'étude simple et directe du comportement des sources continues d'énergie électrique perturbées par les courants harmoniques provenant des charges non-linéaires. En effet, il parait tout naturel d'aborder ce problème, car la plupart des générateurs des sources d'énergies renouvelables produisent un courant continu. La première approche consiste en la modélisation du système à étudier afin d'analyser son comportement vis-à-vis de ces charges polluantes. Une simulation à partir de Matlab-Simulink a permis de prévoir le comportement du système; les résultats de cette simulation ont été donnés sous forme de graphiques. La deuxième démarche s'appuie essentiellement sur le souci de réaliser un contrôle classique et moins onéreux de ces harmoniques à l'aide d'un filtre en comparaison à celui effectué avec un Modulateur à Largeur d'Impulsion (MLI). Enfin, la dernière démarche consiste à choisir les paramètres L et C du filtre afin d'éviter que la fréquence de résonance F_0 de celui-ci ne corresponde à la fréquence d'un harmonique possible du courant. L'onduleur transfère l'énergie produite des modules photovoltaïque dans le réseau en gardant la tension alternative constante.*

Keywords: Simulation - Renewable energy generator - Unbalanced loads - Behaviour.

1. INTRODUCTION

Many papers, in which the generators are considered as noise sources (sources of flicker, harmonics, or higher-frequency components), may be found in scientific reviews studying the impact of dispersed generation on power quality [1-4]. Another perspective for such a study certainly is: What about the connection of 'classical' noisy loads onto a micro-grid fed by renewable energy generators?

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Most power plants fueled by renewable energy sources produce electrical power in direct current (DC) form. Examples include photovoltaic systems, fuel cells and wind power plants with rectifier. The connection of the conventional load to these power plants requires DC/AC conversion.

Solar energy is renewable, clean and inexhaustible. Solar energy systems require little maintenance, are quieter and emit no pollutants. Their economic exploitation sets minimum design and implementation requirements for photovoltaic (PV) power systems. The PV system must be made robust, reliable and highly efficient.

The major problem in the exploitation of PV panels is their non-linear character. The PV module has an optimum operating point, the so called point of maximum power (PPM) that depends on the intensity of the incident illumination.

The adaptation of the PV panel to different loads is therefore necessary in order to extract maximum power from each PV module. This is done using DC-DC energy converters regulated by MPPT controllers, ‘Maximum Power Point Tracking controller’, [2].

The behaviour of the generators with respect to noisy loads obviously depends on the control strategy. With an ideal strategy, a Pulse Width Modulator, ‘PWM’ DC/AC converter will behave like an active power source that eliminates negative sequence currents and voltages, harmonics and other voltage fluctuations.

The analysis of the dynamic behaviour of such a system was done with Matlab-Simulink. The Continuous Equivalent Model was used for the converter (the PWM model would give the same results, because the higher-frequency components due to switching are eliminated by the filter). A first application was made with an unbalanced load (single-phase load connected between two phases).

This study looks into the opposite situation where the control is very basic, i.e. cheap and without any active filtering function. The question has been: What is the ‘natural’ behaviour of the generating unit as compared to the ‘natural’ behaviour of a classical AC source, where the short-circuit impedance is made up essentially of the inductance of the supply transformer?

2. MODEL DESCRIPTION

The system which was modeled by the circuit in figure 1 simply consists of a DC generator connected to a load by a DC/AC converter.

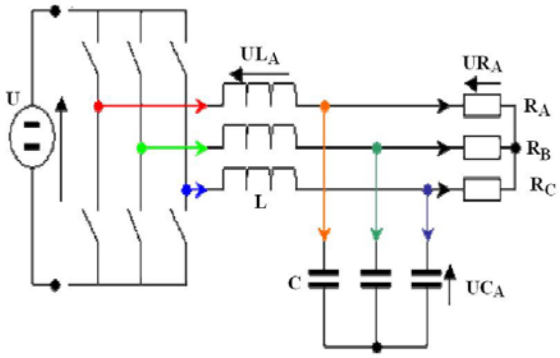

Fig. 1: Electrical system under study

Given that the power absorbed by the load can be expressed as a function of the short-circuit power and the relation between positive and negative sequence voltages by:

$$\frac{S_{load}}{S_{cc}} = \frac{U_i}{U_d} \tag{1}$$

The analytic expression for the short-circuit power of the system can therefore be written as:

$$S_{cc} = S_{load} \times \frac{U_d}{U_i} \tag{2}$$

For this study we consider one of the resistances of the three-phase load to be very big, i.e. near infinity, while the other two are constant and of the same value (that is a typical case of an unbalanced load).

The power absorbed by the load can be determined using:

$$R_a = \infty \qquad \text{and} \qquad S_{load} = \frac{U_{bc}^2}{R_b + R_e} \tag{3}$$

A calculation of the short-circuit power gives the short-circuit impedance as:

$$Z_{cc} = \frac{U^2}{S_{cc}} \tag{4}$$

U is the voltage when the system is running loadless ($R_a = R_b = R_c = \infty$).

The objective of this calculation is to compare the short-circuit impedance Z_{cc} obtained by simulation (i.e. the DC Source-Inverter is working on an Unbalanced Load), with that of a similar system in which the DC Source-Inverter combination is replaced by an AC Source (Z'_{cc}).

3. RESULTS OF SIMULATIONS

The per-phase load voltages, the line-line voltages between phases and the currents in the phases obtained by simulation are shown in Figures 2, 3 and 4 respectively.

Figure 5 shows the variation of the current at the DC side of the converter. In this particular case, the current lies in the interval [0, 8]. We can remark too that, the frequency of this current is twice the supply frequency.

The phase voltages without load are not bigger than half the value of the voltage at the DC side of the converter.

The value of the equivalent short-circuit power is not bigger than 20 kVA in our case. The ratio between positive and negative sequence voltages is about 5 %.

The equivalent short-circuit impedance (given by (2)), gives a value around 1.083 ohm.

On the other hand, the impedance of the filter is given by:

$$Z_L = j\omega L = j(314 \times 3.2e-3) = j\,.\,1\,\Omega$$

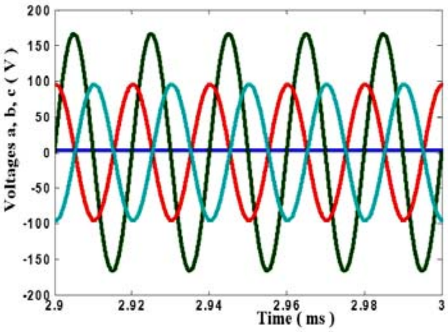

Fig. 2: Per-phase voltages obtained at the phases (a, b, c) of the unbalanced load

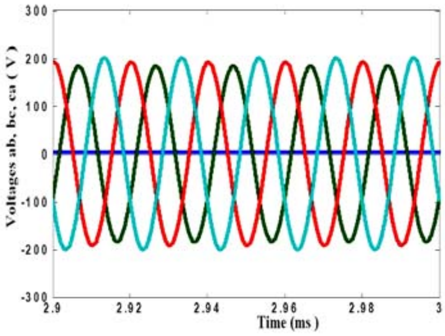

Fig. 3: Line-line voltages between phases (a, b, c) of the unbalanced load

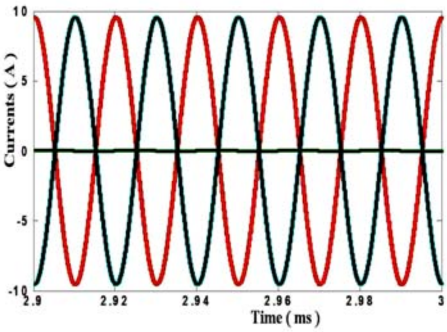

Fig. 4: Load currents at the phases a, b, c

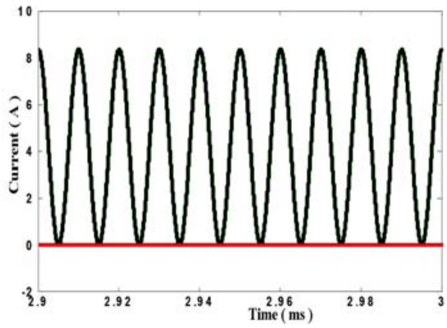

Fig. 5: Current at the DC side of the converter when AC connected to unbalanced load

$$Z_c = 1/(j.\omega.C) = 1/j.(314 \times 31.83e-6) = -j\,.\,100\ \Omega$$

$$Z_{cc} = \left| \frac{L\,\omega}{L.C.\omega^2 - 1} \right| = 1.0101$$

The short-circuit impedance obtained from the result of the simulation (1.083 Ω) is greater than the calculated value from the filter (1.0101 Ω).

Thus, with the simple model which was used for the PWM AC/DC converter (no active filtering function), the 'short-circuit' impedance (Thevenin equivalent) of the generator is practically equal to the impedance of the filter.

The question is then how to choose the parameters L and C (the influence of C being low for 50 Hz, but important at harmonic frequencies)?

4. THEVENIN EQUIVALENT

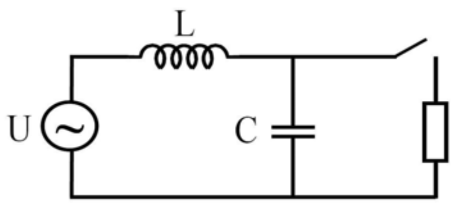

Fig. 6: Thevenin equivalent scheme

Source impedance

$$\left|Z_s\right| = \left|\frac{\frac{\omega L}{\omega C}}{\omega L - \frac{1}{\omega C}}\right| = \left|\frac{\frac{\omega L}{\omega C}}{\frac{\omega^2 LC - 1}{\omega C}}\right| = \left|\frac{\omega L}{\omega^2 LC - 1}\right| \tag{5}$$

At the power supply frequency (50 Hz), $\omega^2 LC << 1$ and $\left|Z_s\right| \approx \omega L$

At the modulation frequencies (5.....15 kHz), $\omega^2 LC >> 1$ and $\left|Z_s\right| \approx 1/\omega C$

A typical value of the reactance of a MV/LV transformer is 4 %.

Therefore, a comparable short-circuit power will be obtained with the PWM generator if $\left|Z_s\right| = Z_{cc} = \omega L = 4\%$, i.e.

$$Z_{cc} = 4\% = \omega L = 0.04\,\frac{U^2}{S_n} \quad \text{or} \quad L = 0.04\,\frac{U^2}{\omega . S_n} \tag{6}$$

5. FILTER EFFICIENCY AT MODULATION FREQUENCIES BETWEEN 5…..15 kHZ

With a modulation frequency of c= n50 Hz, where n = 3, 5, 7,….voltage harmonics are injected in the micro-grid, with frequencies equal to kn50 Hz, where k = 1, 2, 3…

Under these conditions,

$$\frac{U_m}{U} \approx \frac{1/n\,\omega C}{n\,\omega L - 1/n\,\omega C} = \frac{1/n\,\omega C}{\frac{n^2\omega^2 LC - 1}{n\,\omega C}} = \frac{1}{n^2\omega^2 LC - 1} \tag{7}$$

The normal range of limits is 0.1…..0.5 %, which means:

$$n^2\omega^2 LC - 1 \approx n^2\omega^2 LC = 1000.....200$$

Or

$$C = \frac{1000.....200}{n^2\omega^2 L} = \frac{(1000.....200).\omega S_n}{n^2\omega^2\, 0.04\, U^2} = \frac{1000.....200}{0.04}\frac{S_n}{n^2\,\omega U^2} \tag{8}$$

5.1 Resonance

The source impedance is infinite at a frequency of 50 z, so that $r^2.\omega^2.L.C = 1$, or:

$$r = \frac{1}{\omega\sqrt{L.C}} = \frac{1}{\omega\sqrt{L.\frac{1000.....200}{n^2.\omega^2.L}}} = \frac{n}{\sqrt{1000.....200}} \tag{9}$$

Table 1: Harmonic number at resonance (r)

U_m / U	5 kHz	10 kHz	15 kHz
0.1 %	3.2	6.3	9.5
0.2 %	4.5	8.9	13.4
0.3 %	5.5	11.0	16.4
0.4 %	6.3	12.6	19.0
0.5 %	7.1	14.1	21.2

N.B.: Values of r too close to 3, 5, 7, 11 and 13 should be avoided.

5.2 No-load current

The impedance seen by the generator at no-load is expressed as:

$$\left| Z_f \right| = \omega.L - \frac{1}{\omega.C} = \frac{\omega^2.L.C - 1}{\omega.C} \tag{10}$$

The current at no-load is given by:

$$I_f = \frac{V}{Z_f} = V.\frac{\omega.C}{\omega^2.L.C} \approx \omega.C.V \tag{11}$$

The nominal power can be obtained as

$$S_n = \sqrt{3}\,U.I_n = 3V.I_n \tag{12}$$

The relative current at no-load is given by:

$$\frac{I_f}{I_n} = \frac{\omega C U}{\sqrt{3}}.\frac{\sqrt{3}\,U}{S_n} = \frac{\omega C U^2}{S_n} = \frac{\omega U^2}{S_n}\frac{1000....200}{0.04}\frac{S_n}{n^2\,\omega U^2} = \frac{1000....200}{0.04}\frac{1}{n^2} \tag{13}$$

The normal range for $I_f / I_n = 0.01......0.10$

Table 2: Relative 50 Hz current in filter at no-load (I_f / I_n)

U_m / U	5 kHz	10 kHz	15 kHz
0.1 %	2.5	0.63	0.28
0.2 %	1.25	0.31	0.14
0.3 %	0.83	0.21	0.93
0.4 %	0.63	0.16	0.069
0.5 %	0.50	0.13	0.056

N.B.: All values in **Table 2** are too high. This means that $Z_{cc} = 4\%$ (0.04 pu) is too optimistic. The values in **Table 2** are to be divided by 2 with $Z_{cc} = 8\%$, divided by 3 with $Z_{cc} = 12\%$.

6. APPLICATION TO KNOWN MODELS

6.1 Model of the above simulation

- $U = \sqrt{3} \times \frac{1}{\sqrt{2}} \times \frac{220}{2} = 134.7\,V$
- $L = 0.0032$ H
- $L = 0.000032$ F
- $n = 200$ ($f_m = 10\,kHz$)
- $S_n = 134.7^2 / 10 = 1814$ VA = 1.814 kVA

Resulting in

- $Z_{cc} = \omega.L(S_n / U^2) = 2.\pi 50 \times 0.0032\ (1814 / 134.7^2) = 0.10$, i.e.10%
- $U_m / U = 1 / (n^2.\omega^2.L.C - 1) = 0.0025 = 0.25\%$
- Resonance order $r = n.\sqrt{(1/(U_m / U)} = 200 / \sqrt{(1/0.0025)} = 10.5$
- $I_f / I_n = 1 / (U_m / U) / Z_{cc} / n^2 = 1/0.0025/0.10/200^2 = 0.1$.

6.2 Model of imperial college [9]

- $U = \sqrt{3} \times 230 = 398\,V$
- $L = 0.0013$ H
- $C = 0.00005$ F
- $n = 200$ ($f_m = 10\,kHz$)
- $S_n = 398^2 / 5 = 31681\,VA = 31.681$ kVA

Giving

- $Z_{cc} = \omega.L(S_n / U^2) = 2.\pi 50 \times 0.0013\ (31681 / 398^2) = 0.08$, i.e.8%
- $U_m / U = 1 / (n^2.\omega^2.L.C - 1) = 0.0039 = 39\%$
- resonance order $r = n.\sqrt{(1/(U_m / U)} = 200 / \sqrt{(1/0.0039)} = 12.5$
- $I_f / I_n = 1 / (U_m / U) / Z_{cc} / n^2 = 1/0.0039/0.08/200^2 = 0.08$.

7. CHOICE OF FILTER PARAMETERS

The filter parameters L and C result from choice of

- Z_{cc} (pu): the series 50 Hz impedance of the generator, and

- $u_m = U_m / U$ (pu): the accepted relative magnitude of the modulation frequency component

$$L = Z_{cc} \cdot \frac{U^2}{\omega . S_n} \tag{14}$$

$$C = \frac{1}{u_m . n^2 . \omega . L} \tag{15}$$

where
- U = phase-to-phase 50 Hz voltage of the generator (V)
- $\omega = 2\pi f = 2\pi 50$ (rad/s)
- $S_n = \sqrt{3 . U . I_n}$ = nominal power of the generator (VA)
- $n = f_m / f$ = ratio between modulation frequency and power frequency

However, care must be taken about the resonance frequency (i.e. the frequency at which the series impedance of the generator becomes infinite)

$$r = N . \sqrt{u_n} \tag{16}$$

And of the magnitude of the current in the filter at no-load

$$i_f = \frac{i_f}{I_n} = \frac{1}{Z_{cc} . u_m . n^2} \tag{17}$$

If we want to have Z_{cc} as low as possible, we have to accept i_f and U_m as high as possible.

Example

With f_m = 10 kHz, and assuming i_f = 10 % and u_m = 0.5 % gives

$$Z_{cc} = \frac{1}{i_f . u_m . n^2} = \frac{1}{0.5 \times 0.005 \times 200^2} = 0.05$$

It means also $r = n . \sqrt{u_m} = 200 . \sqrt{0.005} = 14.1$ which looks acceptable.

It this case, with U = 398 V and S_n = 30 kVA:

$$L = Z_{cc} \cdot \frac{U^2}{\omega . S_n} = 0.05 \times \frac{398^2}{2\pi 50 \times 30000} = 0.00084 = 0.84\,\text{mH}$$

$$C = \frac{1}{u_m . n^2 . \omega^2 . L} = \frac{1}{0.005 \times 200^2 \times (2\pi 50)^2 \times 0.00084} = 0.00006 = 60\mu\text{F}$$

N.B.: If the modulation frequency is 5 kHz instead of 10 kHz.

$$Z_{cc} = \frac{1}{i_f . u_m . n^2} = \frac{1}{0.1 \times 0.005 \times 100^2} = 0.02$$

On the contrary, if f = 15 kHz, Z_{cc} = 0.022 = 2.2 %.

8. CONCLUSIONS

From the results of equation (17), it can be seen that the achievable short-circuit power strongly depends on the modulation frequency.

In particular, if we set the voltage magnitude of the high frequency (HF) at 0.5 % of that of the fundamental frequency of 50 Hz, and similarly assume a relative magnitude of 10 % for the no-load current in the filter, we obtain a short-circuit impedance of $Z_{cc} = 2.2\ \%$ at 15 kHz, 5 % at 10 kHz and 20 % at 5 kHz.

Results obtained using our MatLab-Simulink models and data from the imperial college confirm its performance.

The model and simulation tools obtained from this work can be used to study the dynamic behaviour of analogue electrical systems.

The result of the study of the dynamic behaviour of this system shows that, the lower the short-circuit impedance (Z_{cc}) is, the higher the no-load current (i_f) and the maximum voltage (u_m) must be.

With the obtained model one observes that the current at the DC side of the inverter has a non-linear form as one would expect for direct current. This explains why there is a diode in the PV circuit. This diode blocks the reverse signal. One can observe current maxima and minima at the DC side of the inverter.

Results obtained using our MatLab-Simulink models show that for some periods of time the unbalanced loads are not supplied by the PV generator (Fig. 5, current minimum equals zero).

This obtained model gives the opportunity to choose filter parameters at different high frequencies.

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