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Harmonic incursion at the point of common coupling due to small grid-connected power stations

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Abstract

The orthodox electric power distribution systems used to be generally radial and direction of flow of power was often from grid towards consumer. Sometimes, the transmission of power generated from newly set small power stations by using transmission network is not feasible due to the transmission losses, service cost on transmission lines and other related issues. That is why, in many cases, small power stations are connected directly to the local distribution network. These small power stations inject active and reactive power to the existing network, badly disturbing the flow of power hence injecting harmonics in the system at the point of common coupling (PCC). This harmonic injection at PCC due to a direct grid-connection of small power stations to the existing large electric power systems is identified. Also, the impact of harmonic incursion by these small generation units is analysed using a straightforward and an effortless method. This simulation based method uses power system components simplified to basic inductive and capacitive elements and can be very helpful for a fast assessment of harmonic incursion at PCC if extended to the practical large inter-connected electric power systems.

Keywords: Point of common coupling (PCC); Harmonic incursion; Electric power systems.

1. Introduction

The analysis of a power system component such as generators, transmission lines and transformers, rely on harmonic voltage and current distortion levels. The harmonic distortion in voltage and current is usually calculated by means of load flow studies with an assumption that power generation and transmission system is perfectly linear. In practice however, the transformer magnetising current harmonics will cause the generator to produce harmonic voltages and currents as harmonic interaction takes place between the rotor and stator circuit of the generator. The process of harmonic

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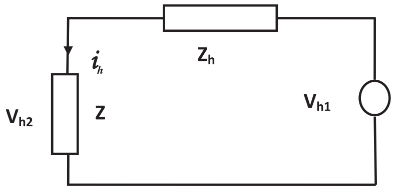

Fig. 1. Thevenin harmonic equivalent of a system.

conversion changes the waveform of the transformer flux which produces distortion in the magnetising spectrum. This new magnetising spectrum results in repetition of the harmonic conversion process at the synchronous generator. Apart from this, any harmonic contribution from any other network component like transmission line, triggers the harmonic interaction between these two nonlinear power system components.

It is hard to analyse the effect of harmonic cross coupling within conventional frames of references. However this is an important characteristic of harmonic formulation and its relevance is evident from harmonic studies. The dynamic analysis of the power system components often needs a detailed model for a certain part of the network, while the rest of the network can be considered an equivalent circuit. In this way the computation efforts required for simulation of the whole network is considerably reduced and simplified.

Short circuit impedance is probably the simplest equivalent model approach at the fundamental frequency. For studies such as fault analysis, this approach is good enough. However for studies where system response should be reproduced at harmonic frequencies, this model cannot approximate the system's behaviour.

The affects of harmonic generating equipment, coupled with system resonance condition are cumulative and can be severe on system operations, if not mitigated. Capacitor banks for reactive power compensation, power converters in variable speed controls of wind turbine generators, FACTS devices and other high power electronic devices used for power system control; are all major causes of harmonic penetration in the system when under resonance condition.

A brief work towards reliable integration of renewable generation by using frequency response characteristics has been carried out in Eto et al. (2010). Presented here, is an attempt towards fast determination of the level of harmonic penetration due to small power stations. An otherwise option to achieve this may be an awful and time consuming programming of typical steady-state power flow software to compute the system frequency response.

2. System's harmonic-impedance

Modelling of systems under harmonic conditions involves the determination of the impedance of the system at harmonic frequencies, as well as the representation of the harmonic sources. The former is determined on the basis of the value of the different elements at power frequency of 50 Hz. The model depends upon a number of things, for instance the accuracy of data and the range of frequency. It is hard to represent the complete system in full in all harmonic studies. The dimensions of the system are therefore reduced to minimum possible scale using the equivalent impedance representing the behaviour of the component to harmonic disturbances. The impedance varies over time and from one point to the other within the system. This variation depends upon the cable length, short circuit power of the system, the VAR compensation and the load level in the system. The measurement of the harmonic impedance of the system is quite difficult to implement. It necessitates the presence of a powerful harmonic current source or a relatively high pre-existing harmonic voltage at the node where the impedance is to be measured (Robert, 1992; Lemoine, 1977).

The pre-existing harmonic or inter-harmonic voltage V_h causes an inter-harmonic current to flow in load Z, as shown in Fig. 1. The pre-existing harmonic or inter-harmonic voltage V_h represents bus bar distortion before any non-linear load is connected e. g distortion due to source impedance. The topic is covered in more detail in Robert (1992) and Lemoine (1977).

The harmonic impedance Z_h is given by:

$$Z_h = \frac{V_{h_1} - V_{h_2}}{i_h} \tag{1}$$

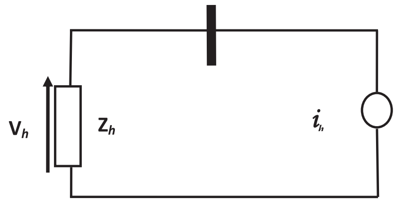

Fig. 2. Determination of harmonic impedance Z_h.

If there is not any harmonic voltage in the system before the injection of harmonic currents by equipment or by use of equipment; the injection (Fig. 2) will produce a harmonic voltage V_h. The harmonic impedance Z_h of stream system viewed from injection point is:

$$Z_h = \frac{V_h}{i_h} \tag{2}$$

In power systems, the system response is equally as important as the source of harmonics. Identification of a source of harmonics is only half the job in harmonic analysis. The response of power system at each harmonic frequency determines the true impact of nonlinear loads on harmonic voltage distortion.

The impedance of the system can be determined by means of analytical computations as long the size of the system is not too large. The impedance of a system is formed of succession of resonances and any resonances which take place mainly due to the cable/transmission line capacitance. If the capacitance is high, these resonances are there at low frequencies (sometimes even at power frequencies). They are also present due to high installed load for VAR compensation.

At the fundamental frequency the power systems are primarily inductive and equivalent impedance is sometimes called simply the short-circuit reactance. The capacitive effects are normally neglected on utility distribution systems and industrial power systems. The inductive reactance of the system changes linearly with the frequency. In power systems, generally do not change significantly with frequency before 9th harmonic.

For lines and cables the resistance varies by square root of the frequency once skin effect becomes significant in the conductor at higher frequencies. At utilization voltages the equivalent system reactance is normally dominated by the in service transformer impedance. An approximation for X_{SC}, based on transformer impedance only is (Dugan, 1987):

$$X_{SC} \cong X_t \tag{3}$$

where

$$X_t = \frac{(kV)^2}{MVA} \times \%Z \tag{4}$$

The equivalent reactance as sum of the ten percent transformers is given in the table. A plot of impedance vs. frequency for an inductive system without any capacitors installed will be a straight line. However the real power systems rarely behave like this. Here the capacitance is neglected which cannot be done for the harmonic analysis. Shunt capacitance either due to cable or due to capacitors at the customer locations for power factor correction on the utility distribution system, dramatically vary the systems impedance with frequency. A severe harmonic distortion can sometimes be endorsed due to their presence. The capacitive reactance X_c is given by:

$$X_c = \frac{1}{2\pi fC} \tag{5}$$

where C is the capacitance. The equivalent line-to-neutral capacitive reactance can be determined by:

$$X_c = \frac{kV^2}{MVAR} \tag{6}$$

One particular worry with harmonics is the resonance condition in the power system. The existence of both inductive components and capacitive components in the system at certain frequencies can cause resonance conditions at point of common coupling or any other bus. If the resonance occurs at a bus where a harmonic current is injected into the system, an overvoltage condition may be observed.

All the circuits containing both inductances and capacitances have one or more natural frequencies. When one of these frequencies, is lined-up with a frequency that is being produced on the power system, resonance can develop in which voltages and currents in the system persist very high values. This is the root of many problems with harmonic distortion in power systems.

At harmonic frequencies, from the perspective of harmonic sources, shunt capacitors appear to be in parallel with equivalent system inductance. At frequencies other than fundamental frequency, the power system generation appears to be as short circuit. When X_c and total system reactance are equal (the difference between X_L and X_c becomes zero), the harmonic currents becomes extremely large. The resonant frequency for a parallel combination of an inductive and capacitive element is:

$$f_{Resonance} = \frac{1}{2\pi\sqrt{LC}} \tag{7}$$

where L is the inductance and C is the capacitance of the network (Lukasz et al., 2009). At high voltages the resistance of a network is more often than not small compared with capacitance and inductance. Therefore, the impedance can change radically. The situation becomes harsh when the resonance frequency matches with the frequency of any harmonic current or voltage. The harmonic current or voltage is amplified, which can cause damage of network components. At this point it is essential to remark that very often resonant frequencies are present between harmonic frequencies (inter harmonic resonance) (Gunther, 2001).

Same system may have several resonance frequencies depending upon the grid configuration. A relatively small distortion at a resonance frequency can lead to overwhelming consequences, which emphasizes the importance of the advance analysis of harmonics. There are two different types of resonances which may occur in the network; parallel resonance and series resonance (Patel, 2010; Wakileh, 2001).

In parallel a resonance, the impedance of a circuit is usually high. In an ideal resonance (the circuit does not have any resistance) impedance becomes infinitely high, which leads to enormously high overvoltage. At parallel resonance frequency, the voltage obtains its uppermost possible value at a given current (Young and Freedman, 2011).

Parallel resonance can occur when a source of a harmonic current is connected to the electrical circuit that can be simplified as a parallel connection of inductive and capacitive component. In an extreme case, even a relatively small harmonic current can cause destructively high voltage peaks at resonance frequency. Parallel resonance is common when there are capacitor banks or long AC lines or cables are connected with large transformers. In this case, large capacitances and inductances start to resonate with each other (Lukasz et al., 2009).

3. A representative study system

A representative study system is devised and cases have been studied for the frequency response characteristics. Important factors affecting parallel resonance are underlined. Simulation is performed based on the data presented in Table 1 for two different cable lengths. The cables are assumed of 25 and 50 kilometres lengths at a capacitance of 0.4 μF/km. Therefore, 10 μF and 20 μF capacitance corresponds to X_c 320 Ω and $X_c = 160$ Ω respectively. The

Table 1
Data for different parameters in Fig. 3(b), used for plots.

Case/Plot No.	T_1 (MVA) $X = 10\%$	T_2 (MVA) $X = 10\%$	X_1 (Ω) $\left(\frac{V_L^2}{MVA}\right) \times 10\%$	X_2 (Ω) $\left(\frac{V_L^2}{MVA}\right) \times 10\%$	L_1 (mH) $X_1/2\pi f$	L_2 (mH) $X_2/2\pi f$
1	5	0.5	2.42	24.2	7.7	77
2	5	1	2.42	12.1	7.7	38.5
3	5	5	2.42	2.42	7.7	7.7
4	10	0.5	1.21	24.2	3.9	77
5	10	1	1.21	12.1	3.9	38.5
6	10	5	1.21	2.42	3.9	7.7
7	15	0.5	0.81	24.2	2.6	77
8	15	1	0.81	12.1	2.6	38.5
9	15	5	0.81	2.42	2.6	7.7

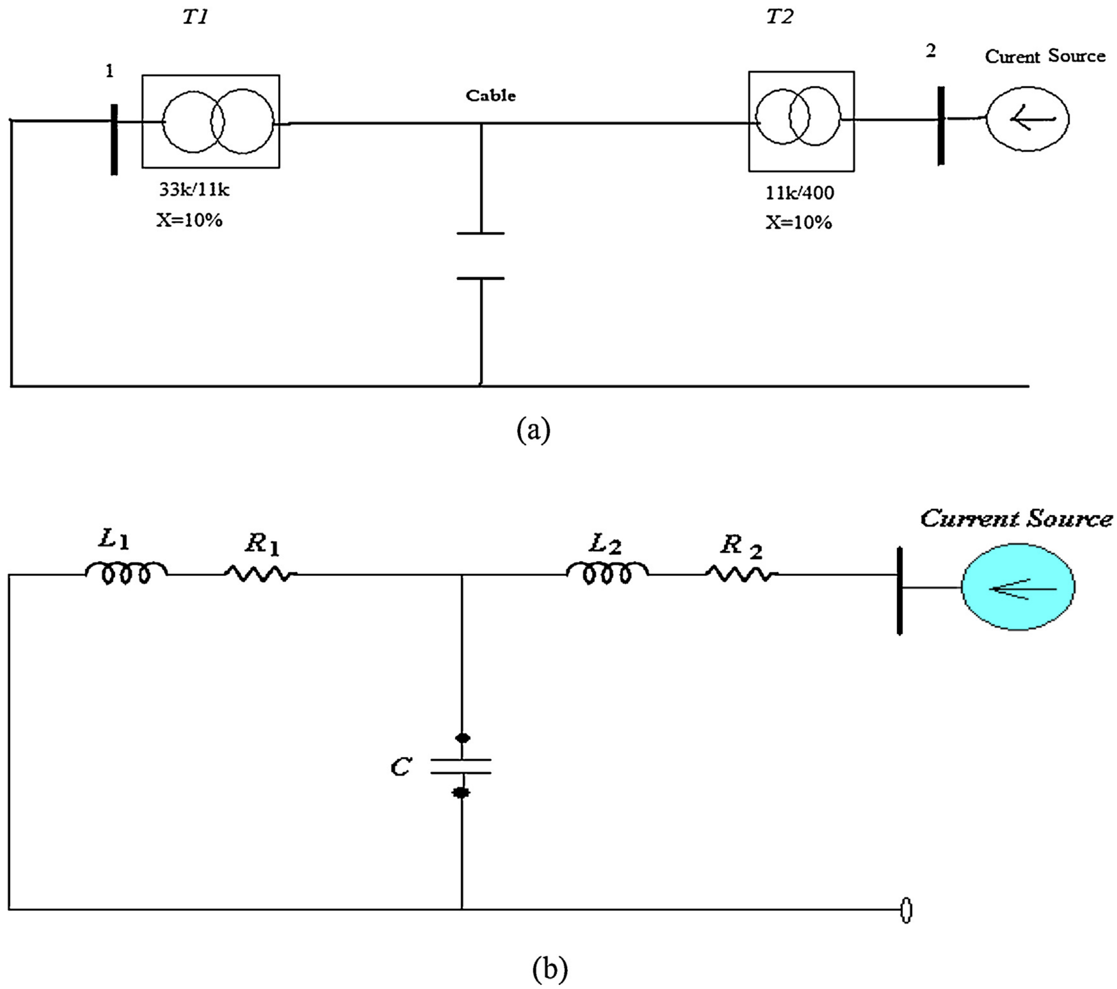

Fig. 3. (a) Cable capacitance in the inductive system. (b) Equivalent.

resistance R_1 and R_2 in the circuit of Fig. 3 are assumed small (0.01 Ω) and correspondingly transferred to 400 V. The transformer is usually a very efficient machine and operates at an efficiency of about 98%; therefore its winding resistance is usually small and so is the case assumed in this discussion.

The parallel resonance in both the cases shown in Fig. 4 is occurring in the same region, 400 Hz and 575 Hz respectively for 50 km and 25 km cable lengths. This indicates that transformer's rating as well as its physical location are the important factors and have significant effect in determining the resonance frequency.

Case 3, in Table 1; is not considered as it can be seen from the transformer ratings that the system with such an arrangement will be un-economical and un-necessary.

The graphs shown in Fig. 5 correspond to Cases 4–6 in the data Table 1. Unlike first three cases the transformer used from 33 kV to 11 kV is a 10 MVA transformer, which indicates a smaller value of inductive reactance. Consequently the inductance in the circuit has shifted to the new position determined by the length of the cable. The resonance frequency varies with cable capacitance. The longer is the length of cable, lower is the resonance frequency. It is also important to notice that the deviation from blue line in Case 5 as well as in Case 6, starts quite earlier than actual peak occurs and continues after the peak has occurred. This explains that the real interval for which harmonic distortion is produced in the system cannot be specified only by the spike due to parallel resonance which can cause severe impact on the quality of the supply voltage.

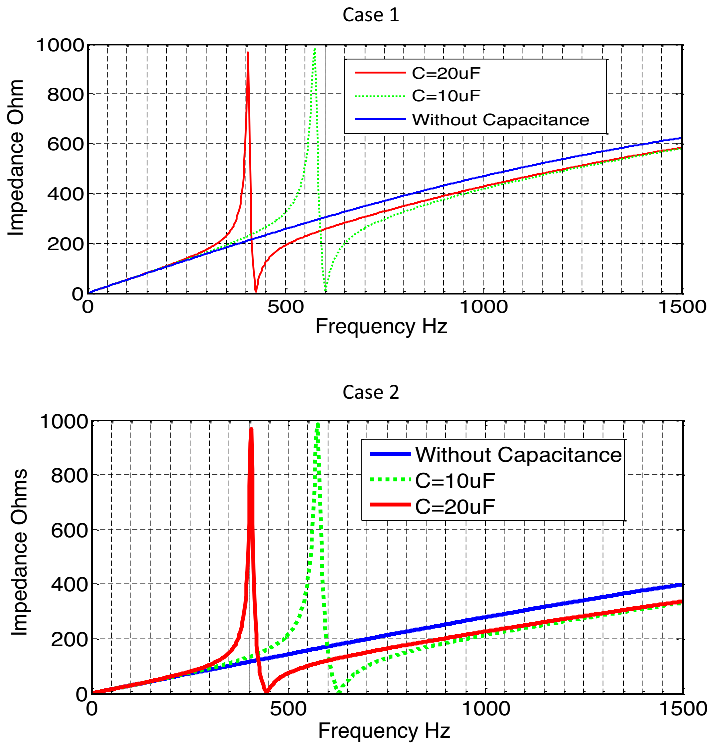

Fig. 4. Frequency response of circuit shown in Fig. 3, Cases 1 and 2, Table 1.

For a certain known resonant condition, given the value of either inductive reactance or capacitive reactance, the value of unknown component can be evaluated. For example, if the resonant frequency is assumed at 500 Hz for Parallel combination of L_1 and C;

$$C = \frac{1}{(2\pi \times 500)^2} \times \frac{1}{L_1} \tag{8}$$

For three values of L_1; 7.7 mH, 3.9 mH and 2.6 mH corresponding to for 5 and 10 MVA transformers and an assumed resonance frequency of 500 Hz, the relevant capacitances are:

$$C_{5\,\mathrm{MVA}} = \frac{1}{(2\pi \times 500)^2} \times \frac{1}{7.7 \times 10^{-3}} = 13.16\,\mu\mathrm{F}$$

$$C_{10\,\mathrm{MVA}} = \frac{1}{(2\pi \times 500)^2} \times \frac{1}{3.9 \times 10^{-3}} = 26\,\mu\mathrm{F}$$

The plots in Fig. 5, demonstrate good agreement with afore calculated respective values of resonant frequencies which substantiate the correctness of simulation process.

Fig. 6 depicts the impact of three different parallel resistances in the same case of parallel resonance in system response characteristics. As little as ten percent resister loading can have a noteworthy and valuable impact on peak impedance. The most troublesome resonant conditions evolve when capacitors are installed on substation buses where the transformer dominates the system impedance and has a high *X/R* ratio. The relative resistance is low and corresponding parallel resonant impedance peak is very sharp and high. This is a common cause of capacitor failure, transformer failure or the failure of other load equipment. It is a misunderstanding that resistive load damp harmonics as in the absence of resonance, load will have little impact on the harmonic currents and the resulting voltage distortion. Most of the current will flow back in the power source. Nevertheless it is appropriate to say the resistive loads damp the resonance hence considerably reducing the harmonic distortion. Motor loads are primarily inductive and provide little damping, rather they may cause an increase in the problem by shifting the resonant frequency closer to a significant

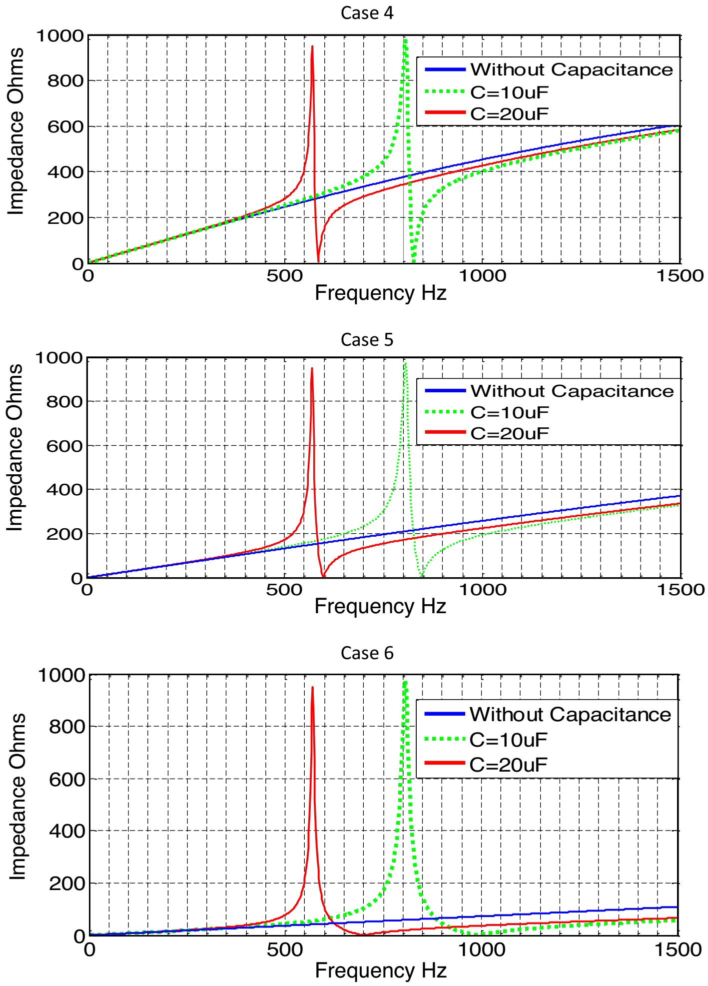

Fig. 5. Frequency response of circuit in Fig. 3, Cases 4–6, Table 1.

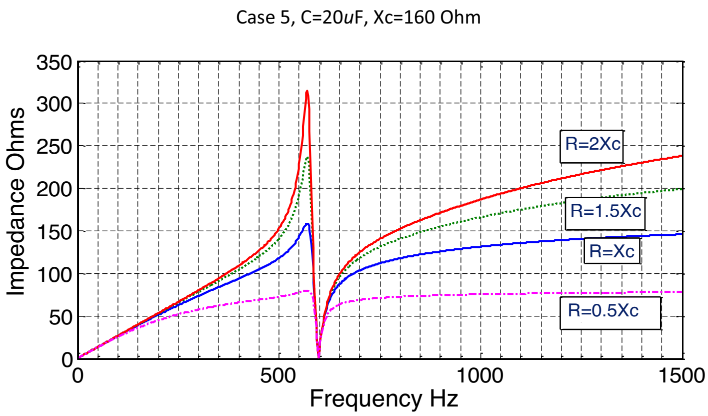

Fig. 6. Effect of parallel load resistance on the frequency response characteristics.

Table 2
Data for components in Fig. 7.

Case/Plot No.	T_1 (MVA) $X = 10\%$	T_2 (MVA) $X = 10\%$	X_1 (Ω) $\left(\frac{V_L^2}{MVA}\right) \times 10\%$	X_2 (Ω) $\left(\frac{V_L^2}{MVA}\right) \times 10\%$	L_1 (mH) $X_1/2\pi f$	L_1 at 400 V (H) Base 400 V	L_2 (mH) $X_2/2\pi f$	L_2 at 400 V (H) Base 400 V
1	5	1	2.42	12.1	7.7	1.02e−5	38.5	5.1e−5
2	15	5	0.81	2.42	2.6	3.4e−6	7.7	1.02e−5

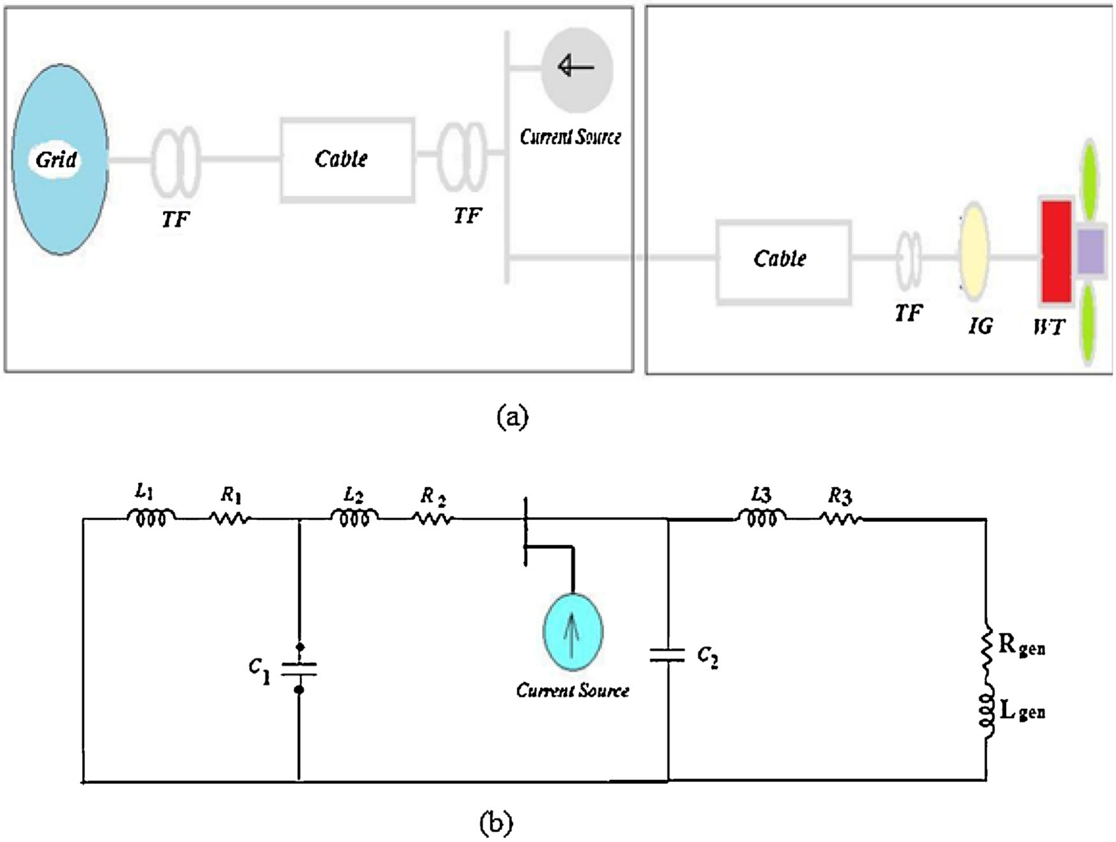

Fig. 7. (a) A generator connected to the system of Fig. 3. (b) Per-phase equivalent.

harmonic. However some small fractional horsepower motors may help in damping because their *X/R* ratio is lower than large three phase motors.

4. Harmonic incursion due to small grid-connected power stations

Small grid-connected plants introduce a great number of non-linear power electronic devices like full scale frequency converters into the grid. The switching operations of the pulse width modulation (PWM) controlled converters are the main sources of both harmonic and inter harmonic currents. Generally speaking, converters create harmonics in the range of a few kilohertz (Tentzerakis et al., 2007). Measuring and controlling these harmonics is one of the greatest challenges of the power quality in small power stations and particularly in wind power plants (Ackermann, 2005). A large number of non-linear power electronic devices can have significant effect on the harmonic emissions. These harmonics can form a serious threat for power quality. That is why harmonic analysis has to be developed and taken as an integrated part of power plant design. Because every power network is unique and has different characteristics, the effect of the harmonics on every power system varies. Nevertheless, some common features can be found. Even if

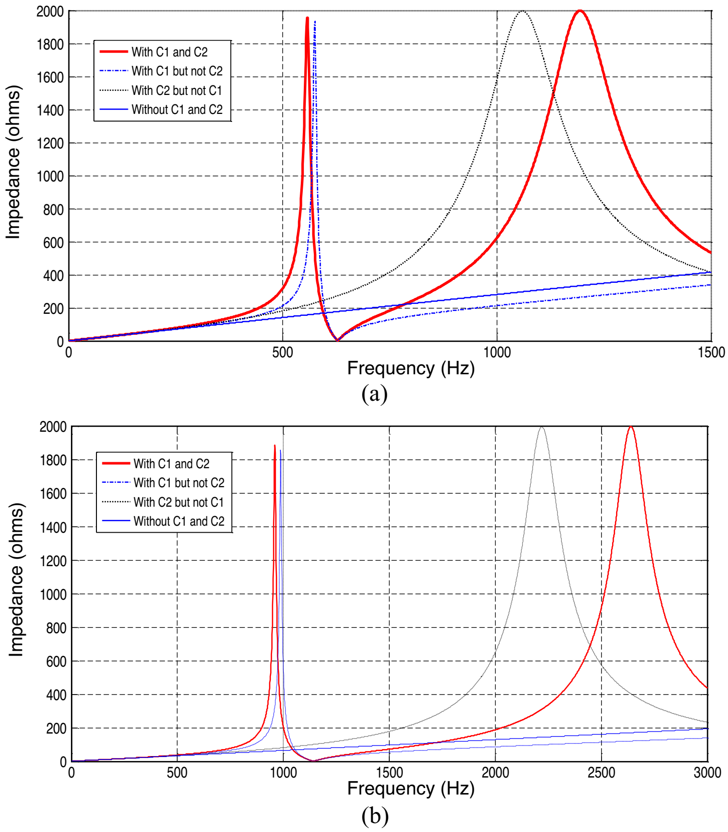

Fig. 8. Response of the circuit shown in Fig. 7. (a) Case 1. (b) Case 2.

the percentage of the harmonics seems small, the harmonic emission becomes a significant issue when the capacity of a grid-connected power plant is hundreds of megawatts.

Every small power plant has its own resonance frequency that is dependent on the grid topology, associated generators and reactive power apparatus used (Fox et al., 2007). Furthermore the impedance and the resonance points of the plant may also change when the number of turbines and capacitor banks in operations changes.

Capacitor banks are commonly used to compensate reactive power and to help improving the power factor in the power system network. Many times, there is a capacitor bank at each turbine as well as at the point of common coupling (PCC) (Heier, 2006). The capacitor banks in the individual turbines are used also. Starting capacitors are also in use in induction generators. Large wind power plants with even hundreds of turbines have a great number of different switching options for the capacitor banks.

There can also be shunt reactors connected to transmission cable terminations to compensate the high capacitance of the cables. These reactors are inductive components that may be adjustable and equipped with a tap changer. The reactors can be connected to the same switch together with the cable connection (Shewarega et al., 2009).

The induction generator is most widely used machine in wind-based power plants. Depending upon the size and location of wind power station, many times they are connected to 11 kV bus bar in the main network. Therefore the system's response has been investigated with the addition of an induction generator (Table 2 and Fig. 7) and its effect on parallel resonance is analysed. Unlike Table 1, only two different cases are dealt here.

The generator is assumed to be a, 500 kVA, 440 V, 50 Hz and *Xper-phase* = 0.8 Ω. It is also assumed that the machine is not a self start one and uses a capacitor bank to start i.e. *Cstarting* = 200 μF. Further that, the generator is connected to 11 kV bust through a cable of relatively small length and a transformer with rating similar to transformer T2 in Table 2. The whole arrangement and its equivalent circuit diagram are shown in Fig. 7. As the effect of starting capacitor when transferred to the secondary side of the transformer is small; the corresponding capacitance in the circuit is rounded-off to a small value of 0.5 μF together with cable capacitance feeding generator power to the grid.

The response of the circuit under both cases of Table 2 is given in Fig. 8. A comparison of these wave-shapes with the corresponding cases of Table 1, shows that there is a huge distortion in waveform beyond about 600 Hz; an indication of the impact of grid-connecting a generator with main system due to parallel resonance caused by the presence of collector cable and feeding transformer. This clearly shows that small grid-connected power stations can cause a severe harmonic incursion.

5. Conclusions

A change in the length of the collector cables moves the resonance frequencies. As a general rule, the greater the capacitance of a capacitive element is, the lower are the resonance frequencies. What must be considered is that the cables do not resonate alone since they need an interaction with an inductive element to create a resonance. Typically this element is a (electrically) local transformer due to its large inductance. The number of resonances is likely equal to the number of physical and equivalent capacitors (cables, capacitor banks etc). The effect of capacitive elements on resonance appears to be decoupled. Each capacitive element contributes to a resonance. There are no "joint" resonances.

In the end, the effect of adding small wind-based units at the PCC is surveyed. Presently, most variable speed generators are connected to the PCC through power electronic converters which act as a source of harmonic injection. Fixed speed wind units on the other hand, use power factor correction capacitors which can shift previously calculated resonance frequency values, hence causing severe distortion in current as well as voltage waveforms.

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