# THE EFFECTS OF WIDESPREAD USE OF POWER-ELECTRONIC BASED DG ON GRID POWER QUALITY

Mahnaz YOUHANNAEI
Electric power distribution Co.– IRAN
myouhannayee@gilanpdc.ir

Hossein MOKHTARI
Sharif univercity of technology – IRAN
mokhtari@sharif.edu

Adham SHARIFI
Electric power distribution Co. - IRAN
power72sharif@yahoo.com

## *ABSTRACT*

*With the higher penetration of Distributed Generation (DGs) into power system, power electronic converters are commonly used as interface to the grid. Power-electronics based DGs are connected to the grid via L, LC or LCL filters To deal with harmonic components. But, these filters create harmonic resonances. This paper presents the effects of grid topology and parameters on resonance-frequencies. Some grid parameters such as impedance, upstream short-circuit levels, filter cut-off frequency have been considered. The system presents a more challenging picture where low order harmonics appear in the grid. First, a single-inverter grid is modelled by the Norton method. Then, it will be extended to multiple-inverter grid, and the resonance-frequencies are analyzed. The model has been evaluated by simulation.*

*Index terms: Distributed Generation, inverter, LCL filter, resonance, Norton model, frequency domain analysis.*

## INTRODUCTION

The use of distributed generation (DGs) units has increased due to technical, economic and environmental benefits, however some drawbacks such as power quality issues, complicated in grid design, operation, control and protection should be considered. Power-electronics based DGs are connected to the grid via L, LC or LCL filters. But, these filters create harmonic resonances [1-3]. The most important issues especially for inverter-based DGs, is low frequency resonance.

In 2004, Resonance was introduced seriously in a large project in Netherlands. The inverters tripped when the background distribution conditions were maximum allowable EN50160. Also all inverters followed IEC61000-3-2 standard but power quality problems have been observed [4]. Therefore inverter topology, control method and output filters are investigated differently. The results showed low frequency resonance made the problems. In this project, a simple passive model without a control system has been used to evaluate resonances. There are several methods to study the inverters performance, such as open-loop transfer function matrix method [1] and the output impedance [6]. According to filters effects, inverters and grid specification, resonance issues of parallel filters can be investigated well-night [5, 7]. Resonant frequencies can be determined by frequency analysis. The resonance appears in both mode, islanding and grid-connected mode [3]. But the effects of widespread use of filters have not evaluated yet.

In [9], a micro grid model using discrete time-domain closed-loop Norton's equivalent circuit was presented. Then multiple resonances, one steady state and other transient resonances, were evaluated. In [10] the resonances and unstable oscillations caused by such interaction, are identified through the impedance-based stability analysis.

This paper presents the effects of grid topology and parameters on resonance-frequencies. Some grid parameters such as impedance, upstream short-circuit levels, filter cut-off frequency and inverter switching frequency have been considered. Then the effects of widespread use of DGs have been studied. First, a single-inverter grid is modelled by the Norton method. Then, it will be extended to multiple-inverter grid, and the resonance-frequencies are analyzed. The model has been evaluated by simulation. In the first part of the simulation, DGs and gridconnections are consideration same. Then, feeders' impedances are changed and complex resonances are analyzed.

## CONFIGURATION OF INVERTER-BASED MICROGRID

Fig.1 shows the block diagram of an inverter-based DG connet to the grid.

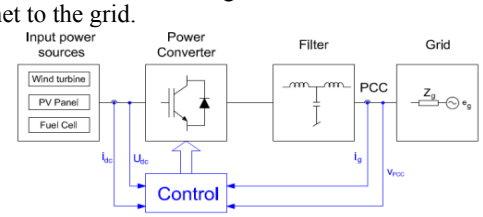


**Fig 1 block diagram of an inverter based DG[12]**

Pulse width modulation (PWM) is usually used controlling the converters and L, LC and LCL filters eliminate high-frequency harmonics. LCL filter is more attractive for two reasons: first, it eliminates high order harmonics better than other. Second, LCL filter have higher power density.[11]. But LC and LCL is the main reason to produce and inject the harmonics to grid [11]. Fig.2 illustrates the circuit of a three element filters that connected to the inverter output [12].

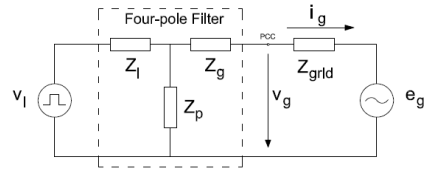


**Fig 2 Circuit configuration of LCL filter [12]**

According to Fig.2 Zg, Zi and Zp are grid-impedance,

inverter-impedance and the capacitance respectively.
Fig.3 shows the bode diagram of Fig.2. It illustrates Series and parallel resonances happen in this grid. The most important issue is that resonance frequencies are low and close to the grid frequency.

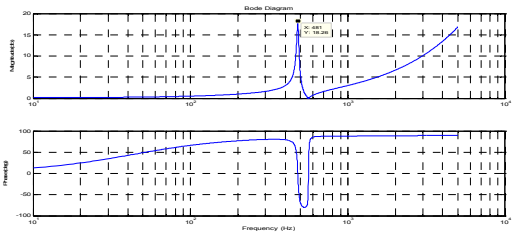


**Fig 3 bode diagram of a grid with single DG**

## RESONANCE FREQUENCY SENSIBILITY ANALYSIS

In this section, frequency resonance sensibility of single inverter microgrid is assessed based on three factors , network impedance, up-stream short circuit and switching frequency afterwards filter cut-off frequency. Circuit parameters are listed in table 1.

**table 1 circuit parameters of single-phase microgrid**

| parameters | symbol | values |
|---|---|---|
| Inverter side inductor | $L_1$, $R_1$ | 3 mH , 0.25Ω |
| Filter capacitor | $C_2$ | 40μF |
| Line side inductor | $L_2$, $R_1$ | 0.2mH , 0.05Ω |
| Grid impedance | $L_{GRID}$, $R_{GRID}$ | 1.4 mH, 0.1Ω |
| Gird voltage | $V_{GRID}$ | 220 v |
| DC link voltage | $V_{DC}$ | 360 v |
| Switching frequency | $F_{SW}$ | 12050 Hz |
| DG nominal power | P | 50 Kw |
| Short circuit level | $VA_{SC}$ | 4 MVA |

The grid is low voltage and it may support different loads but loads effects are neglected. Resonance frequency equation is shown in (1) and it should be satisfied (2) [13-14].

$$f_{resonance} = \frac{1}{2\pi}\sqrt{\frac{L_1+L_2}{L_1 L_2 C_2}} \quad (1)$$

$$10f_1 < f_{resonance} < \frac{1}{2} f_{SW} \quad (2)$$

Where $f_1$ is the grid voltage frequency and $f_{sw}$ is the switching frequency. In order to let the high-frequency harmonic pass through the capacitor path, the switch frequency impedances $X_{c2}$ must be about 0.1~0.2 of $X_{L2}$.

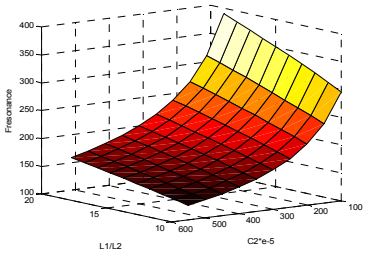


**Fig 4 variation of resonance frequency vs. filter elements**

If in (1), $L_2$ replace with $L_2+L_g$, grid resonance frequency will be obtained. so resonance frequency is a function of $L_g$. So bigger $L_g$ will make resonance frequency smaller.
If in equation 1 the amount of $L_1+L_2$ is supposed constant, then resonance frequency will be a function of $C_2$ and $\frac{L1}{L2}$. Then assuming $C_2$=10~100 $\mu$f and $\frac{L1}{L2}$=10~20, fig 4 shows variation of resonance frequency versus $C_2$ and $\frac{L1}{L2}$. When the value of $\frac{L1}{L2}$ is fixed, bigger $C_2$ will makes resonance frequency smaller. When $C_2$ is fixed, smaller $\frac{L1}{L2}$ will make resonance frequency smaller. When low cut-off frequency is selected, filter resonance will be close to grid low order harmonics and grid may be unstable.

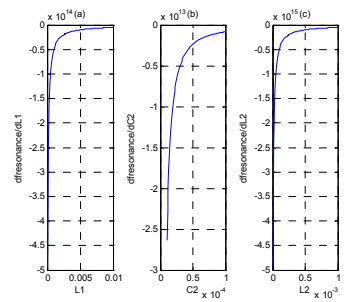


**Fig 5 variation of resonance frequency vs. filter element, (a) dFres/(dL1 ), (b) dFres/(dC2 ) ,(c) dFres/(dL2 )**

Fig.5 show that resonance frequency sensibility versus inductances is less than capacitance. Generally, inverter-side inductance is chosen several times bigger than grid-side. Even $L_2+L_g$ is smaller than $L_1$. So sensibility of resonance frequency versus $L_2$ is more than $L_1$.

## resonance frequency sensibility simulation

In this section, a single inverter micro grid according to table 1 is simulated to verify the results of the previous part. $L_g$ varies from 1 to 10 mH. Fig.6 shows Grid bode-diagram versus $L_g$ on the filter output bus . It shows that Resonance frequency follows grid impedance. Further more If DG places far from the PCC, resonance frequency will be closer to grid frequency. Therefore, in order to locate inverter-based DG not only the usual parameters must be noticed but also the resonance frequency should be considered.

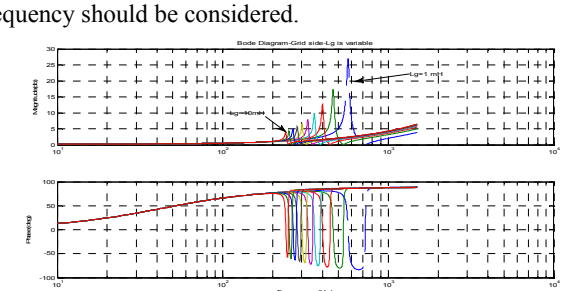


**Fig 6 Grid bode-diagram vs. Lg ($V_{PWM}/i_{g1}$ ), filter output bus**

If $i_{g1}$ trigger DG output voltage, bigger $L_g$ make smaller resonance amplitude. It's the result of network damping influence. According to fig.7 , resonance frequency

become more by bigger short-circuit current. So resonance problem is more seriously in weak grid. But the effect of short-circuit level is less than grid impedances. If $L_g$ and short-circuit level vary 10%, resonance frequency will respectively vary 6% and 10%.

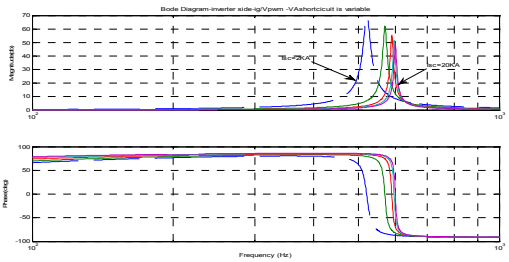


**Fig 7 Grid bode-diagram vs. up-stream short circuit current ($V_{PWM}/i_{g1}$), filter output bus**

The third factor that effects on resonance frequency are switching frequency afterward filter cutoff frequency or filter components. First, five filters designed for different switching frequencies, then system bode diagram plotted for each.

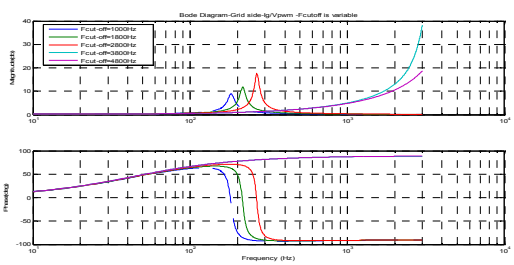


**Fig 8 Grid bode-diagram vs. filter cutoff frequency ($V_{PWM}/i_{g1}$), filter output bus**

It should be noticed that if rated power of DG increase, filter cutoff frequency must be chosen less, due to technical issue of power switches. Fig.8 presents variations of resonance frequencies versus filter cutoff frequencies. The smaller cutoff frequency will make resonance frequency smaller. Also there is a nonlinear relation between filter cutoff afterward filter components and resonance frequencies. When cutoff frequencies increase, resonance frequencies increase more. So, to select filter cut-off frequency in inverter-based DG microgrid, it must be noticed resonance frequencies.

## WIDE SPREAD USE OF INVERTER-BASED DG ON DISTRIBUTION NETWORK

In this section, a grid with N inverter-based DG has been modelled and analysed.

### Modelling of grid with N inverter-base DG

In a grid with N inverter-based DG, $L_1$ and $L_2$ are inverter-side and grid-side inductance respectively and $C_2$ is filter capacitance. Impedance of sub feeder is shown as $L_g$ and $R_g$. Meanwhile, the microgrid mainfeeder impedance is desired as $R_{grid}$ and $L_{grid}$. There is no controller in the system. In the single DG microgrid, transmission function of $I_{g1}$ will be as:

$$I_{g1}(s) = H_1(s).V_{PWM}(s) + H_2(s).V_{PCC}(s) \qquad (3)$$

In which

$$H_1 = \frac{1}{L_1LCs^3+(R_gL_1+R_gL)Cs^2+(L_1+L+CR_1R_g)s+R_1+R_g} \qquad (4)$$

$$H_2 = \frac{L_1Cs^2+R_1Cs+1}{L_1LCs^3+(R_gL_1+R_gL)Cs^2+(L_1+L+CR_1R_g)s+R_1+R_g} \qquad (5)$$

The $V_{PWM}$ and $V_{PCC}$ are inverter output voltage and voltage of the PCC and $I_{g1}(s)$ is the line current. By adding a controller, the general analyzes is the same but computation will be changed. $H_2(s)$ indeed is the equivalent inverter admittance and $H_2(s).V_{PWM}$ will suppose as a dependent current source. Thus equivalent Norton circuit for the single inverter system will be obtained. In a micro grid with N different parallel inverters, there will be N number of $V_{PWM}$s and N parallel admittances. $L_2$ admittance is connected to the network via Ygrid. Using Kirchhoff law line current and Vpcc can be obtained as (6):

$$V_{PCC} = \frac{\sum_{i=1}^{N} H_i(s).V_{PWM,i}(s)+V_{grid}(s).Y_{grid}(s)}{\sum_{i=1}^{N} Y_{eq,i}(s)-Y_{grid}(s)} \qquad (6)$$

Then line current is in hand using equations 3 and 6 as below:

$$I_{g1}(s)=R_1(s).V_{PWM1}(s) + \sum_{t=2}^{N} P_{1,t}(s).V_{PWM,t}(s) - S_{G,1}(s).V_{grid}(s) \quad (7)$$

Equation 7 shows that there are three separated and independent parts in first inverter current ($I_{g1}$) or there should be three types of resonances in the network. The first part is $V_{PWM1}$ motivated resonance and the second and the third one are resonances that are motivated by $V_{grid}$ and $V_{PWM,t}$. elements of equation 7 can be get using circuit analyzing methods as below:

$$R_1(s) = G_1(s) + \frac{Y_{eq1}(s).G_1(s)}{\sum_{i=1}^{N} Y_{eqi}(s)-Y_{grid}(s)} \qquad (8)$$

$$P_{1,t}(s) = \frac{Y_{eq1}(s).G_t(s)}{\sum_{i=1}^{N} Y_{eqi}(s)-Y_{grid}(s)} \text{ و } t \in [2,N] \qquad (9)$$

$$S_{G,1}(s) = \frac{-Y_{eq1}(s).Y_{grid}(s)}{\sum_{i=1}^{N} Y_{eqi}(s)-Y_{grid}(s)} \qquad (10)$$

To analyze a micro grid with a lot of inverters, matrix equations are rewritten as equation 11.

$$\begin{bmatrix} I_{g1}(s) \\ I_{g2}(s) \\ \cdots \\ I_{gN}(s) \end{bmatrix} = \left( \begin{bmatrix} R_1(s) & P_{12}(s) & \cdots & P_{1N}(s) \\ P_{21}(s) & R_2(s) & \cdots & \cdots \\ \vdots & \vdots & \vdots & \vdots \\ P_{N1}(s) & P_{N2}(s) & \cdots & R_N(s) \end{bmatrix} \times \begin{bmatrix} V_{PWM1}(s) \\ V_{PWM2}(s) \\ \vdots \\ V_{PWMN}(s) \end{bmatrix} \right) - \left( \begin{bmatrix} S_{G1}(s) \\ S_{G2}(s) \\ \vdots \\ S_{GN}(s) \end{bmatrix} \times V_{grid}(s) \right) \qquad (11)$$

It is clear, in weak grids , non-diagonal elements of matrix are not zero and parallel inverters interact each other. But in a strong grid impedance is close to zero and inverters are decoupled. Total current of main grid will be as equation 12.

$$I_g(s) = \sum_{i=1}^{N} i_{gn} = \sum_{n=1}^{N} 1 \left(\sum_{m=1}^{N} K_{nm}(s)\right).V_{PWMn} + n=1NSGns.Vgrid \qquad (12)$$

In (12), when $n = m$, $K_{nm}$ is equal to $R_n$, and if $n \neq m$, then it will be $K_{nm}=P_{mn}$.

## Simulation of multiple-inverter grid

In this section a two-DG grid has been simulated and resonance frequency has been investigated. To make the discussion easier, it is assumed that all the inverters and feeders have same parameters which can be find in Table1.

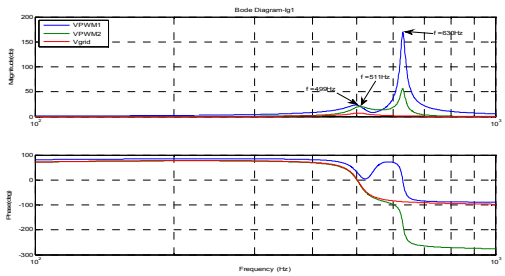


**Fig 9 Two-DG grid bode-plot -$V_{PWM1}$, $V_{PWM2}$ and $V_{grid}$ vs. $i_{g1}$**

Fig.9 shows bode-plot of $V_{PWM1}$, $V_{PWM2}$ and $V_{grid}$ versus $i_{g1}$. As illustrated, three resonance peaks are appeared. According to (7), one of them is called series resonance and is determined by all inverter and grid impedances. It's exited by grid voltage. There are two types of resonance which are new and are introduced as self and mutual resonances. Self-resonance is introduced by transfer function of $\frac{ig1}{VPWM1}$ and mutual-resonance is defined by transfer function of $\frac{ig1}{VPWM2}$ .This resonance is triggered by $V_{PWM2}$. In the other hand, $V_{PWM2}$ excites the current harmonic of $i_{g1}$.

**Inverter and feeders have same parameters**

Fig. 10 illustrated the bode diagram of a micro_grid with different numbers of inverter-based DG. Circuit has been simulated in four situations. In the first case one inverter connect to the grid and the next states, respectively, two, four and eight inverters come into the network.

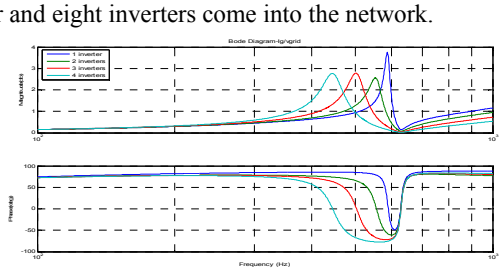


**Fig 10 bode-diagram of multiple-DG microgrid- grid bus ($V_{grid}/i_g$)**

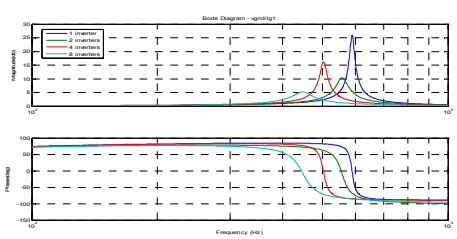


**Fig 11 bode-diagram of multiple-DG microgrid-($V_{grid}$ /$i_{g1}$)**

As shown, when the inverter numbers are more than one, the frequency response shows two resonance peaks. One of them is fixed and the other moves to the low frequency part by increasing the number of DGs. According to second part of equation 12, it will be obtained:

$$\frac{V_{grid}}{i_g} = Z_{grid} - \frac{1}{N} . Z_{eq1} \qquad (13)$$

First part of (13) is independent of inverter number and the second part depends on N. Amount of transfer function is increased by augmentation of inverter numbers.

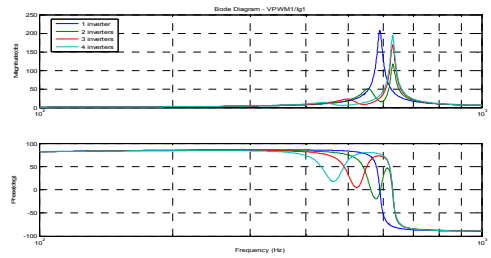


**Fig 12 bode-diagram of multiple-DG microgrid-inverter bus($V_{PWM1}$ /$i_{g1}$)**

Fig.10 shows micro-grid bode-diagram with different number of inverters at the inverter bus. System equation is obtained as (14). In this situation, there is only one resonance peak in the bode diagram which moves to low frequency part with the increased number of inverter. But the amplitude of response peaks are decreased. In other words, damping is increased.

$$\frac{V_{PWM}}{i_g} = \frac{1}{G_1} . \frac{N.Z_{grid} - Z_{eq1}}{(N^2 - N + 2).Z_{grid} - Z_{eq1}} \qquad (14)$$

The load of case3 is less than other situation. As result peak amplitude is increased. So when grid load is off-peak, resonance amplitude is increased. It is necessary to design flexible damping system to control the resonances.

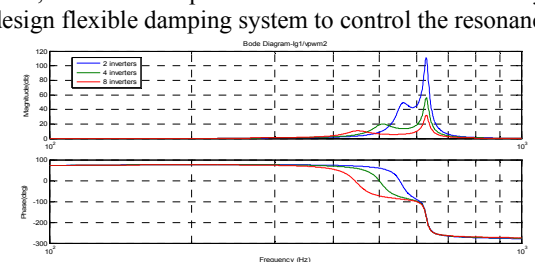


**Fig 13 bode-diagram of multiple-DG microgrid-($V_{PWM2}$ /$i_{g1}$)**

Figs. 10 and 11 show one resonance peak and two peaks are appeared in Figs. 12 and 13 due to different observation point. When bode- diagram of point 1(grid side) is plotted, only two main branches are observed. In this case one resonance peak is calculated. But when bode-diagram of point 2(inverter side) is drawn, three main branches can be seen consequently two resonance frequencies are computed. More over, circuit natural frequency is related to independent inductors and capacitors [15]. Point 2 has one independent element more than point 1. It's clear that two resonance peaks will be appeared at point 2.

**Feeders impedances are different**

Zero-pole maps of for-inverter system with different line impedances are shown in fig 19.

When all parameters of inverters and lines are same, zeros and poles of system are close together and only two resonance peaks will be appeared in bode-plotted.

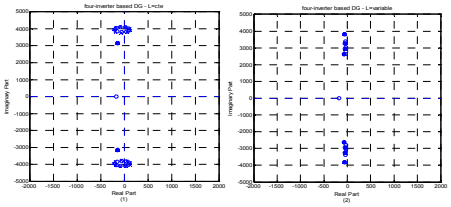


**Fig 14 bode-diagram of four-DG microgrid (1) similar line impedances. (2) Different line impedances**

But when one of parameters will be different, zeros and poles separate each other and all resonance peaks are shown in bode-plot according to fig 14.

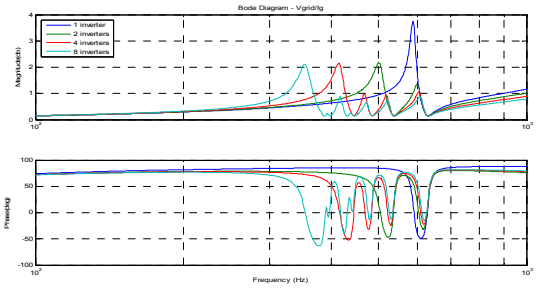


**Fig 15 bode-diagram of multiple-DG microgrid-variable line impedances -grid bus (Vgrid/ig)**

In sub-feeder, there are a self resonance, a series resonance and N-1 mutual resonances. In main feeder, there are a series resonance and N mutual resonances.

## CONCLUSION

In this paper, resonance frequency sensibility of single inverter microgrid is assessed based on three parameters, and then the effect of widespread use of inverter-based DG in distribution networks has been studied. The following conclusions are made by analysis and simulation.

- Resonance frequency follows grid impedance. Further more If DG places far from the PCC, resonance frequency will be closer to grid frequency. Inverter-side bode-plot of system shows that amplitudes increase when resonance frequencies decrease. It is important to design damper.
- The resonance-frequency will increase as the PCC S.C.R increases. Therefore, resonance-frequency may become a problem in weak grid. But the effect of the S.C.R is less than grid-impedance.

Lower filter cutoff frequency will make smaller resonance-frequency. Also there is a nonlinear relation between them. According to the sensitivity of the resonance-frequency versus LCL filter components, the resonance-frequency is more sensitive to the filter inductance as compared to the capacitance.

- if the rated power of the DG increases, switching frequency and output filter cut-off frequency will also be lowered.
- There are three resonance types in a grid with more than one inverter-based DG. One is the series resonance which is determined by the inverter and the grid impedances. This resonance is exited the by grid voltage or current harmonics. The others two resonances are introduced as the self and mutual resonances. The crucial point is that these resonance frequencies moves to the low frequency part with increased the number of inverters

-In a sub-feeder, there are a self-resonance, a series resonance and N-1 mutual resonances. In the main feeder appears a series resonance and N mutual resonances.

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