# HIGH FREQUENCY INTERACTION OF POWER ELECTRONICS CONVERTERS IN AC AND DC POWERED DATA CENTERS

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## Abstract

There has been an increase in the number of data centers due to the increase in the requirement of IT services in recent years. While data centers supplied by AC are an established industry, data centers supplied by DC are more research based. Many industries have set up small and experimental DC data centers. In both AC and DC data centers, power electronic converters are employed to supply continuous and reliable power to the servers. The paper aims to study the interaction of these converters in their switching frequency regions within data centers. The paper focuses on beat frequency oscillations caused by high frequency interaction and the impact of cable length on beat frequency.

## 1 Introduction

Data centers are primarily used for housing data processing devices and their paraphernalia. It also includes the power conversion and backup equipment to maintain reliable power as well as environment control equipment [1]. The end load of the data center power chain is the data processing device, i.e., the server. Traditionally the data centers were powered by AC, but the server is essentially DC powered and each server has its power supply unit. To reduce the power conversion steps research has been done to establish a DC powered data center [2]. The power conversions in the data centers are facilitated using power electronics converters. A continuous interaction of these converters can lead to system instability and power quality issues [3], [4]. This happens due to resonances between the output filters and the operating frequencies of the converters. In data centers, many converters operate in cascaded or parallel connection. E.g. UPS (AC or DC) acts as a source to the server power supply units (PSU), making it a cascaded connection with UPS acting as the source converter and server PSU as load converter. Due to requirement for continuous availability of power, redundant UPS are working in parallel. UPSs' are also connected in parallel to meet the system power capacity requirement. The operation of converters in cascaded and parallel leads to possible interaction in high frequency region caused by their switching frequencies [5]. This interaction could lead to the presence of low frequency oscillation in the AC or DC link supplying the servers and is referred to as beat frequency oscillation [6]. A low oscillation voltage appears at the input of the PSU and propagates to the output of the PSU. It is amplified by the feedback loop gain, which leads to interference in the duty cycle generation of the converters, and also causes a circulating AC ripple current to flow between the converter input filters [7] leading to mal-operation of the converters. In data centers, the servers are most vulnerable to such oscillations as they operate at low voltage DC. The authors in [8] have reported an example of the beating between two UPS systems switching at 4 kHz in an office building. The beat frequency oscillation in this case caused audible chirping noise. In DC micro-grids, where more than one converter is connected to the same DC bus, their operation needs to be synchronised. Due to natural coupling between converters, a beat frequency oscillation occurs on DC bus. This leads non-synchronised operation of converters causing a risk of system instability [9].

This paper aims to show the possibility of the presence of beat frequency on AC and DC link under various operating conditions in a data center. The AC or DC link cable parameters influence the magnitude of the beat frequency. The paper also aims at studying the impact of cable length on beat frequency and its propagation.

## 2 Beat frequency in converters

Power electronic converters, operating at slightly different switching frequencies, the switching frequency acts as a sinusoids and a beat frequency oscillation is introduced [10]. In distributed power systems, one converters switching frequency ripples are other converters perturbations. Consider two converters connected in series or parallel. Converter 1 has a switching frequency fs1 and converter 2 is switching at fs2. Both the converters are switching using PWM technique and the switching frequencies fs1 and fs2 differ very slightly. PWM techniques superimpose the switching frequency and its multiples in the output voltage and current of the converters. Thus, when perturbations with frequencies k2 fs2 (k2 = 1,2,..) are injected into converter 1, whose switching frequency is fs1, the output voltage of converter 1 will contain multiple components at frequencies k2 fs2 and $f_{beat} = |k_1 f_{s1} - k_2 f_{s2}|$. Similarly, the output voltage of converter 2 contains multiple components at frequencies k1 fs1 and $f_{beat} = |k_2 f_{s2} - k_1 f_{s1}|$. These components relate to the difference between the two switching frequencies, and they are called beat frequency components. When they obtain considerable high magnitudes, there will be oscillations in the voltage bus.

The magnitude of the beat frequency voltage is dependent on the equivalent series resistance (ESR) of the capacitor and the magnitude of injected perturbations by both the converters [5]. The beat frequency magnitude also depends on the value of the cable impedance that is connecting the two converters. The cable impedance damps the beat frequency oscillations. In all the previous works, the impact of cable impedance is neglected. Thus, the aim of the paper is to present a simple model to study the beat frequency propagation in data center for different grid-configurations and to show the impact of cable impedance

### *2.1. Data center layouts and beat frequency*

The internal grid of a data center can be either AC or DC. Both types of data centers are primarily supplied by a utility. The supply voltage can be either 480V, 60Hz or 400V, 50 Hz. Fig. 1. shows the block diagram of a conventional power chain in an AC data center [4]. As seen in Fig. 1, the power supplied by the utility reaches the server rack via a UPS. The UPS first converts AC power to DC, and then inverts it. It also includes a battery backup. The server rack and UPS are connected through a cable, its length depends on the size of the data center and the configuration of the internal grid. The server rack consists of several servers arranged in a stack. At the rack level, the AC power is distributed among servers. Each server has its PSU, which then converts the AC voltage to regulated DC. Each PSU employs an AC-DC and DC-DC converter. In this paper, a 3-phase AC system is considered. To maintain the high availability requirement, the UPSs' are often arranged in N+1, N+2, 2N, and 2N+1 redundancy [1]. In this paper N+1 redundancy is considered, so two UPS with the same power rating are connected in parallel. If the UPSs' have some dissimilarity in their switching frequency, beat frequency will appear in voltage and current at the cable connecting them. Additionally, if the PSU and UPS have slightly dissimilar switching frequencies a beat frequency can occur between them. The prior case is due to parallel connection of converters and the latter is due to cascaded connection. For a DC data center in Fig. 1, DC-DC converter replaces the AC-DC converter in the UPS and the server power supply will now consist only of DC-DC converter. A DC UPS is employed to convert the AC supply to DC using a power factor corrected (PFC) rectifier and DC-DC converter. A battery is connected to the DC link, which acts as a back-up supply. A separate charge controller can be installed to charge a battery. The DC power is supplied to PSU, which further steps down the DC link voltage to a lower voltage level needed for the server. The DC UPS and the PSU are connected in cascaded manner, beat frequency can be found on the DC link voltage and current. Considering, the N+1 criteria, if the DC UPS are connected in parallel beat frequency will occur. Thus beat frequency can occur under conditions similar to mentioned in AC data center.

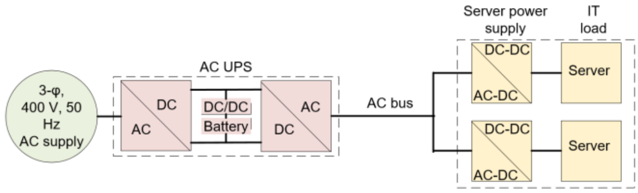


Fig 1. Internal layout of AC data center

## 3 Simulation Results

### *3.1. DC data center*

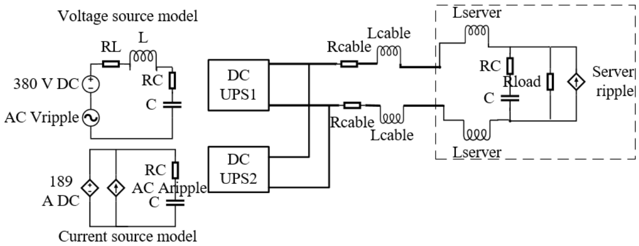


Fig.2. Simulation model representation for DC data center

Table 1. Parameters used in the simulation

| Parameters | Values | Parameters | Values |
|---|---|---|---|
| $V_{dc}$ | 380 V | C, RC | 500 µF, 264.5 mΩ |
| $I_{dc}$ | 189.47 A | L, $R_L$ | 400 µH, 1.4 mΩ |
| Power | 72 kW | C, RC(server) | 3300 µF, 80 mΩ |
| ΔV | 1 % | $L_{server}$ | 6.9 µH |
| ΔI | 5 % | Rload | 2.2 Ω |
| $R_{cable}$, $L_{cable}$ | 0.236 Ω/km, | $f_{s1}$, $f_{s2}$ | 20,000 Hz, 20,010 Hz |

The DC data center is represented by the circuit shown in Fig. 2. The system parameters are given in Table 1. The rating of server is assumed 800 W [11]. A single server is supplied by two PSUs, each capable of supplying the server alone. Both the PSU are employed simultaneously sharing 50% of the load. Each rack is assumed to have 10 servers, making each server rack to be 8000 W and there are 9 racks in total. As shown in [12], the beat frequency is dependent on the value of capacitor and it's ESR. The magnitude of beat frequency in the output voltage of server PSU is also dependent on the control loop parameters (not considered here). The server is represented by inductance *L* in series with a parallel combination of capacitor *C*, load resistance *R* and switching frequency component as shown in [13]. The capacitor represents a combined value of capacitance for all server PSUs. A voltage source or current source and its output impedance represent the DC UPS. Two DC UPS are operating in parallel to satisfy the N+1 criteria, each capable of handling the load in case of failure. Hence, they share 50 % of the load. Bulk resistance $R_{cable}$ and inductance $L_{cable}$ represent the DC link cable. A three-core AC cable can be used, with one core connected to +, second core connected to – and third core can act as PE [14]. The cable selected is 10 kV, 3×120 AKKJ cable, which is capable of carrying 225 A rms or equivalent DC current [15]. The cable is chosen based on the current it is required to carry. To observe the effect of cascaded converters and parallel converters, two scenarios are considered.

*Cascaded operation of DC data center:* The first scenario is to observe beat frequency in cascaded operation when both DC UPS have the same switching frequency ripple $fs1$ = 20,000 Hz and the server rack i.e. the load has $fs2$ = 20,010 Hz. Here the source converter DC UPS is represented using a voltage source model shown in Fig. 2. The server rack is the load converter. It can be seen from Fig. 3, that the 10 Hz beat frequency component is superimposed on the DC link voltage near the source converter. The beat frequency is magnitude is calculated as a variation from peak to zero crossing of the waveform. The magnitude of the beat frequency is 0.031 V and 0.028 V for 1 and 10 m respectively. The beat frequency is 30% that of the high frequency ripple seen in DC link voltage. The beat frequency component in DC link current is present in both cases, and its amplitude is 0.027 A and 0.025 A, for 1 m and 10 m cable, which is approximately 9 % of the ripple current. For 1 m cable, DC link voltage at the load converter does not differ much compared to the voltage at the source converter terminal. For 10 m cable, the amplitude of beat frequency component is 0.021 V and the high frequency component is around 0.4 V, making the beat frequency component 4.5 % of the high frequency ripple. The cable resistance amplifies the magnitude of the switching frequency ripple voltage whereas the beat frequency being low frequency is damped by the cable inductance. Hence, for a longer cable length the beat frequency present in DC link voltage is damped.

*Parallel operation of DC data center:* The second scenario is to observe beat frequency in parallel operation when both the DC UPS have slightly different switching frequencies. The switching frequency of DC UPS1 fs1 = 20,000 Hz and DC UPS2 = 20,010 Hz, while the switching frequency emitted by rack PSU is assumed to be 50,000 Hz. For parallel operation, the current source model shown in Fig. 2 is used. Fig. 3 shows the results for a 10 m long cable. The rack emission can be seen in the voltage and current at the load terminal, but is absent at the source converter terminal. For 1 m and 10 m cable length, the voltage at the source terminal has 1.3 V of high frequency distortion and the beat frequency envelope is 50 % of its magnitude. At the load terminals, the voltage is damped by 0.05 V due to 1 m cable, and it is reduced by 0.5 V for 10 m cable. The magnitude of current ripple present at converter terminals is higher than in the bus current.

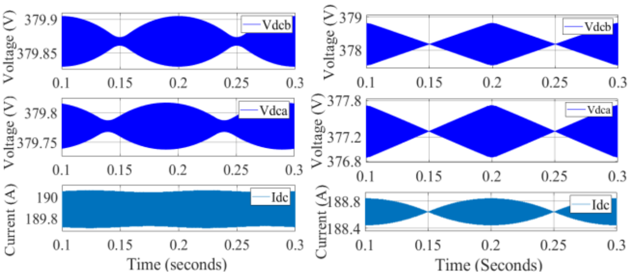


Fig.3. Vdc before and after the cable, Idc of the bus for 1 m and 10 m long cable for cascaded (left) and parallel operation (right) respectively.

## 3.2. *AC data center*

A model similar to the DC data center as shown in Fig.4 represents the AC data center. A single-phase system is considered for simulation assuming that the other phases behave similarly. Since, the total system power 72 kW is divided among three phases, a single-phase AC system is designed for 24 kW. The parameters used are given in Table 2 and the cable parameters are kept the same. The AC UPS acts as a source converter. Since the UPS has an inverter in the output, the output LC filter parameters are calculated for the inverter according to [16]. The 9 racks are divided equally among the three phases and the server filter parameters are adjusted accordingly as given in Table 2.

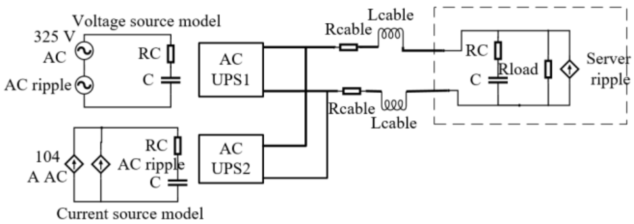


Fig.4. Simulation model representation for AC data center

Table 2 Parameters used in the simulation

| Parameters | values | Parameters | values |
|---|---|---|---|
| $V_{AC}$ | 325 $V_{pk}$ | $R_{cable}$, $L_{cable}$ | 0.236 Ω/km, 0.32 mH/km |
| $I_{ac}$ | 147 $A_{pk\text{-}pk}$ | C, RC | 355 µF, 200 mΩ |
| Power | 24 kW | C,RC(server) | 1100 µF, 240 mΩ |
| ΔV | 1 % | Rload | 4 Ω |
| ΔI | 5 % | $f_{s1}$, $f_{s2}$ | 20,000 Hz, 20,010 Hz |

*Cascaded operation of AC data center:* The AC UPS is assumed to be switching at fs1 = 20,000 Hz and the server is switching at 20,010 Hz. It is assumed that only one AC UPS is supplying instead of two parallel UPS. When two UPS were connected the beat frequency was damped 10 times. It can be seen from Fig. 5 (left) that the beat frequency appears as an envelope superimposed on the top and bottom part of AC waveform. To show it, the top part of the AC waveforms are shown and the beat frequency envelope is highlighted in the waveforms. The results are shown in Table 3. From the results it can be concluded, that while the increase in cable length leads to decrease in the beat frequency magnitude for current it increases the magnitude of voltage beat frequency.

Table 3 Results of cascaded converter

| Cable | 1 m | | | 10 m | | |
|---|---|---|---|---|---|---|
| Para meters | (a) | (b) | (c) | (a) | (b) | (c) |
| Vacb (V) | 656 | - | - | 656 | - | - |
| Vaca (V) | 654.8 | 656 | 0.17 | 650 | 653 | 0.4 |
| Iac (A) | 302.5 | 318 | 5.1 | 291 | 295 | 1.4 |

Pk-Pk Amplitude = (a); Pk-Pk Amplitude with Beat frequency (b); (b- a)/a in % = (c)

*Parallel connection of AC data center:* The parallel operation is observed between the two AC UPS. It is assumed that AC UPS1 is switching at 20000 Hz and AC UPS 2 is switching at 20010 Hz. To see the impact of beat frequency on parallel operation, it is assumed that the server is not injecting any switching residue. The simulations were made with a 1m cable and 10 m cable. Fig.5 (right) shows the currents drawn by UPS connected in parallel for 1 m long cable. Since the beat frequency is caused by the UPS connected in parallel, the envelope can be observed on the AC voltage at the source terminals. The envelope is also observed at the server (load) terminals, and the cable impedance does not damp it much. The beat frequency has higher impact on the AC current, and is seen as superimposed on the top part of the current waveform. The currents shared by UPS shows the complete envelope of beat frequency. The impact of variation of beat frequency can be observed at the top part of envelope. The impact of change in cable length on beat frequency is tabulated in Table 4. It can be seen from the results that, with the increase in the cable length the beat frequency at the source terminal increases from 0.18% for 1m cable to 0.31 % for 10 m cable. Since the increase in the cable length leads to an increase in impedance, the beat frequency is damped at the load terminals in both the voltage and current.

Table 4 Results of parallel converters

| Cable | 1 m | | | 10 m | | |
|---|---|---|---|---|---|---|
| Parameters | (a) | (b) | (c) | (a) | (b) | (c) |
| Vacb (V) | 656.7 | 658 | 0.18 | 656.7 | 658.8 | 0.31 |
| Vaca (V) | 656.6 | 658 | 0.17 | 657 | 657.1 | 0.06 |
| Iac (A) | 290.8 | 296 | 1.65 | 290.6 | 292.1 | 0.5 |

Pk-Pk Amplitude = (a); Pk-Pk Amplitude with Beat frequency (b); (b- a)/a in % = (c)

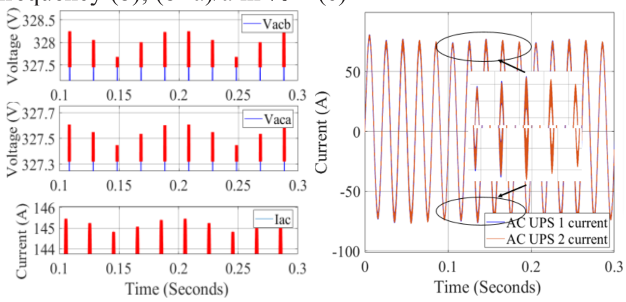


Fig.5. Vac before and after the cable, Iac of the bus for 10 m long cable for cascaded operation (left) ; Currents drawn by UPS connected in Parallel (right)

## 4 Cable length vs beat frequency damping

A relation of damping in beat frequency verses increase in the length of cable is presented in this section by using the MATLAB curve fitting tool. The case of cascaded operation of DC data centers shown in Section 3.1 is considered for this study. The inductance and the resistance of the conductor are considered proportional to the length of the conductor. An increase in the length of conductor adds resistance and inductance between the source and load converter. Simulations were performed by increasing the cable length, and the voltages at the source, load and cable current were measured. The measurements were done for both the beat and ripple frequency. Fig. 6 (left) shows the variation in beat frequency for voltage before and after the cable, with the increase in the length of cable. It was found that beat frequency decreases exponentially with the increase in the cable length, but remains constant after certain length.

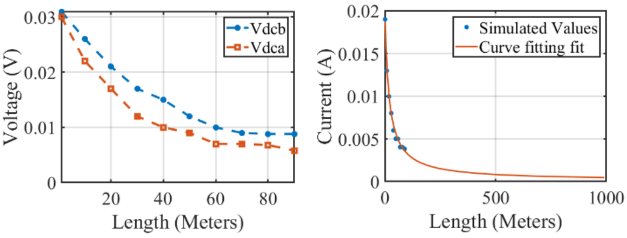


Fig. 6. Variation in beat frequency with the change in cable length in (left) voltage and (right) current

Using the MATLAB curve fitting tool box, the relationship can be described by equation (1)

$$F(x) = \frac{p1 * x + p2}{x + q1} \qquad (1)$$

Where *p1*, *p2*, *p3* and *q1* are coefficients (with 95% confidence bounds) derived by curve fitting tool box and *x* is the change in the length of the conductor. The results are presented in Table 5. A comparison between the simulated values and the curve fitted values for bus current is shown in Fig. 6 (right). The fitted curve is extended up to 1000 m, to show that the beat frequency is damped, but does not become zero.

Table 5 goodness of fit

| | Parameters & Bounds | SSE | R^2 |
|---|---|---|---|
| Iac | P1 = 8.988e-5 (-6.2e-5,2.02e-5)<br>P2 = 0.384 (0.29,0.45)<br>Q1 = 19.52 (14.07,22.97) | 8.1e-7 | 0.99<br>63 |

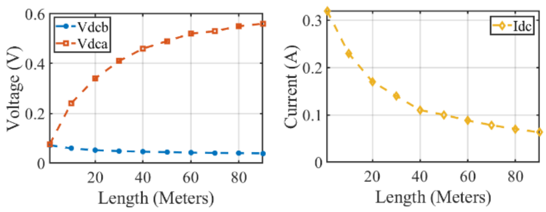

Fig.7. Variation in the switching frequency ripple with the change in cable length for voltage (left) and current (right)

It can be seen from Fig. 7 that for an increase in cable length, the switching frequency ripple almost remains constant for the voltage before cable, but increases for the voltage measured after the cable. This ripple increases, but remains constant after a certain length. The current ripple decreases with the increase in cable length.

## 5 Conclusion

The presence of large number of converters makes data centers susceptible to various power quality issues. Since it is a complex system a lot of them remain unidentified. The beat frequency due to interaction of various converters in their high frequency region, is one of them. A simple model to represent beat frequency on supply bus was presented. The paper showed the cascaded and parallel conditions, which can cause beat frequency oscillations. The paper showed the impact of change in cable impedance on the beat frequency. It was found that for cascaded operation, the beat frequency oscillation impacts the bus voltage rather than the bus current. When the cable length is increased, the beat frequency reduces, but the switching frequency ripple increases. The beat frequency being low frequency reduces due to increase cable inductance (impedance) with the increase in its length. The cable inductance causes a phase shift between the beat frequency voltage before and after the cable. The value of cable inductance and the cable length affects the magnitude of shift. The phase shift between the two voltages can be a measure for the distance between the sources that cause the beat frequency. This phase shift can also be seen between voltage and current at the load terminals. For parallel converters, since both the converters were emitting switching frequency of the same magnitude, the beat frequency magnitude was found to be half the high frequency magnitude. The increase in the cable length damped beat frequency oscillation. For converters connected in parallel, the impedance of the cable connecting them is assumed small. The AC or DC cable inductance, does not impact the phase of the beat frequency in case of parallel converters as they are on the same side of the cable.

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