Analysis on the Effect of Capacitor Banks Operation towards Total Harmonic Distortions (THD) in Distribution Network Test System

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Abstract

This paper purposely to examine and analyse the impact of the distribution capacitors banks operation to the transition of total harmonic distortion (THD) level in distribution network system. The main advantage of this work is the simplicity algorithm of the method and the system being analysed using free access open software which is known as electric power distribution system simulator (OpenDSS). In this paper, the harmonic current spectrum which is collected from the commercial site was injected to a node point on IEEE13 bus in order to provide the initial measurement of THD for the network. The proper sizing of the capacitors banks has been set and being deactivated and activated throughout the network to see the transistion in the THD level in the system. The results were achieved by simulation of the data on the configured IEEE13 bus. The simulation work was done by using the combination of C++ source codes, OpenDSS and Microsoft Excel software. From the output results, the THD current has increased up to two times from the initial value in certain phases and for the THD voltage, the THD has increased up to three times from its initial value in all phases.

Keywords: Distribution capacitors; Resonance; Total Harmonic Distortion (THD); Harmonics; Power Factor

1.0　INTRODUCTION

In any operation of power distribution network, it requires proper equipment configuration for the network in a way to assure the good quality of its performance. The placement of capacitors banks is one of the normal configuration in normal design of electrical power distribution. Generally, the purpose of the capacitors is to significantly reducing power loss, enhancing the voltage stability, compensating reactive power and correcting the power factor within the system [1]. The major operation of the capacitors banks is to correct and improve the power factor to be remained close to unity. But despite to its function, the operation of these capacitors can give displeasure impacts and produce numerous problems such as transient, nuisance tripping and most importantly magnifying the total harmonic distortions (THD) which already have existed in the network system even right before the capacitors being connected to the system. The THD could be excessively magnified due to the nature operation of the capacitors that can produce resonance condition especially when they combined with the short-circuit impedance [2-4]. In this paper, the case study will show the how the operation of the capacitors banks has increased the total harmonic distortion to the extent that can seriously harm the whole network system. The main advantage of this work was the accessibility of the network configuration which available in the Opendss software. Other than that, the application of the real data from commercial building enable the network to be analysed under real condition of harmonic current spectrum. Hence, the output results be able to provide an analysis based on real scenarios of a network system. At the end of this paper, an analysis on the impact from the operation of the capacitor banks towards the increment in total harmonic distortion is expected to prove the hypothesis.

2.0 METHODOLOGY

The IEEE13 node buses schematic diagram as in the Figure 1 has been chosen to implement the case study for this work. Each of node bus on the schematic were either in single phase (1∅) or in three phase (3∅) configuration system setting. As shown in the figure, there were two units of capacitor banks been setup at 611 node bus and also at the 675 node bus. These alignments were purposely to provide a series connection between the capacitors and the harmonic current spectrums source. Thus from there, the effect of series resonance could be occurred which led to the magnification or transition in the harmonic distortion.
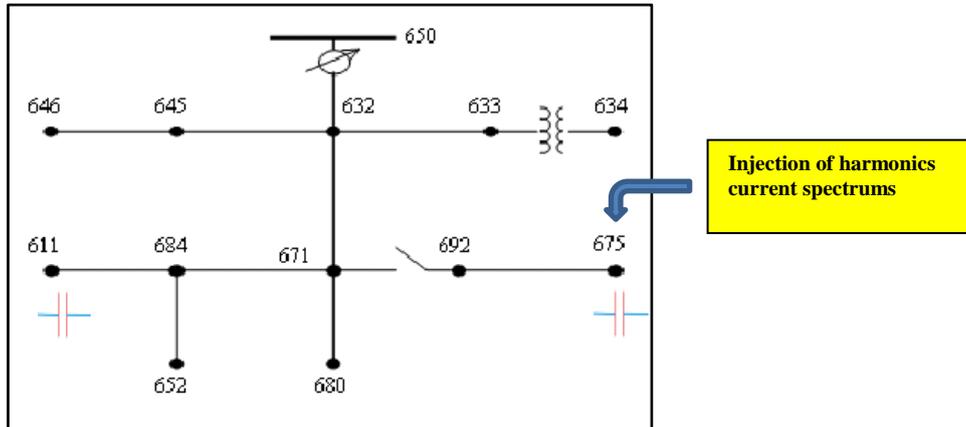
Figure 1. The injection of harmonics current spectrums at node 675 on IEEE13 bus test system

The idea of this work was to inject the harmonic current spectrums on the selected node bus before and after the capacitor banks being connected to the system. The purpose was to prove the hypothesis that the operation of both capacitor banks could give impact to the existed harmonic distortion level in the network system. To be clarified, the 611 node bus was setup for 1∅ system meanwhile the 675 node bus was setup for 3∅ system. The harmonic current spectrums were collected from the commercial building for one-week period started from 10 February 2010 until 16 February 2010. Then, the harmonic spectrums on 13 February 2010 were chosen to be injected to the 675 node bus network system. The selection of the harmonic spectrums on that particular date was simply because it was on working day hours and the harmonic currents were expected to be generated at higher value.

2.1 Size of capacitor banks

As for the capacitor banks, their size has been setup to match with the rated power for each 611 node bus and 675 node bus as can be seen in Table 1. The size of the capacitor banks was determined by the consecutive formula below:

▫ Power factor

$$\cos \theta = \frac{Real\ power, P}{Apparent\ power, S} \tag{1}$$

▫ Size of capacitor, Qc

$$Qc = P \tan \theta \tag{2}$$

Table 1. The size of the capacitor banks that have been set up for the node buses

Node	V line, V (kV)	Real power, P (kW)	Rated reactive power, Qr (kVar)	Cap banks size, Qc (kVar)
675 a	4.16	485.0	190.0	191.73
675 b	4.16	68.0	60.0	18.9
675 c	4.16	290.0	212.0	51.5
611	2.4	170.0	80	109.32

*The subscripts a, b, and c represent phase a, phase b and phase c for the $3\emptyset$ system at   675 node bus.

2.2 Total of harmonic distortions and harmonic order

In the perspective of harmonic distortion analysis, the following formulas of total harmonic distortion for current and voltage (THDi and THDv) respectively were used in the calculation.

▫ Total current harmonic distortion, *THDi*

- $$THDi = \frac{\sqrt{\sum In^2}}{I_1} \qquad (3)$$

▫ Total voltage harmonic distortion, *THDv*

- $$THDv = \frac{\sqrt{\sum Vn^2}}{V_1} \qquad (4)$$

As mentioned earlier, the connection between the capacitor banks and harmonic current spectrums source in series would induces a resonance which then became the main factor for the harmonic distortion to be magnified. Thus for this paper, in order to determine which harmonic order that has being magnified, the formula of resonance frequency shown below was used.

▫ Resonance frequency, fr

- $$fr = fs \sqrt{\frac{S\,sc}{Q\,r}} \qquad (5)$$

Where,

- fs = the system frequency
- $S\,sc$ = the short circuit power (kVA) at the point where the capacitor is to be connected
- Qr = the rated reactive power

▫ Harmonic order, H

$$H = \sqrt{\frac{fr}{fs}} \qquad (6)$$

2.3 Related international standard

In any research work, the output results must be referred to related international standard in order to see the compliance of the results to the standard. As for this paper, the IEEE Std. 519-2014 for voltage and current distortion depicted in the Table 2 and Table 3 was used as a reference [11].

Table 2. Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
V ≤ 1.0 kV	5.0	8.0
1 kV < V ≤ 69 kV	3.0	5.0
69 kV < V ≤ 161 kV	1.5	2.5
161 kV < V	1.0	1.5^a

[a] High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected. [5]

Table 3. Current distortion limits for systems rated 120 V through 69 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a, b]						
I_{SC}/I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD
< 20[c]	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

[a]Even harmonics are limited to 25% of the odd harmonic limits above.

[b]Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

[c]All power generation equipment is limited to these values of current distortion, regardless of actual Isc/IL. Where,

Isc = maximum short-circuit current at PCC

IL = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions [7].

2.4 Flowchart of research work

Finally, the flowchart below has shown the sequential steps in order to get the output results for this case study.

```
┌─────────┐
│  Start  │
└─────────┘
     │
     ▼
┌──────────────────────────────┐
│ Select on which IEEE test    │
│ systems of distribution      │
│ network configuration and    │
│ components to be used        │
└──────────────────────────────┘
     │
     ▼
┌──────────────────────────────┐
│ Inject the harmonic current  │
│ spectrum from commercial     │
│ building to the test system  │
└──────────────────────────────┘
     │
     ▼
┌──────────────────────────────┐
│ Execute simulation work and  │
│ analyse results of harmonics │
│ (without capacitor connected)│
└──────────────────────────────┘
     │
     ▼
   ( A )
```

```
   ( A )
     │
     ▼
┌──────────────────────────────┐
│ Set up the parameters for    │
│ distribution capacitors and  │◄──┐
│ activate the operation of    │   │
│ both capacitors in the test  │   │
│ system                       │   │
└──────────────────────────────┘   │
     │                             │
     ▼                             │
┌──────────────────────────────┐   │
│ Execute simulation work and  │   │
│ analyse result of harmonics  │   │
│ (with capacitor connected)   │   │
└──────────────────────────────┘   │
     │                             │
     ▼                             │
    ◇ Any changes? ◇──── No ───────┘
     │
    Yes
     ▼
┌──────────────────────────────┐
│ Compare and analyse the      │
│ simulation of THD results    │
└──────────────────────────────┘
     │
     ▼
┌──────────────────────────────┐
│ Calculate the resonance      │
│ frequency and harmonic order │
└──────────────────────────────┘
     │
     ▼
┌─────────┐
│   End   │
└─────────┘
```

Figure 2: Flow chart of research work

3.0 RESULTS AND DISCUSSION

3.1 Power factor correction

As in the introduction part, one of the main functions of capacitor banks applied to the network system were to improve the power factor of the system. Hence, in this case study, Table 4 showed the value of the improved power factor when the capacitor banks operated at both 611 node bus and 675 node bus.

Table 4. The improved power factor at the node buses

Node	Before power factor correction	After power factor correction
675 a	0.93	No need to be corrected
675 b	0.75	0.9
675 c	0.81	0.9
611	0.43	0.85

3.2 Total harmonic distortion

On the other hand, despite the benefit of the capacitor banks that has improved the power factor, the resonance effect has started to give impact on the total harmonic distortion. This can be best observed throughout the plotted THDi and THDv graphs in Figure 3 until Figure 6 which showed the comparison of the THD level before and after the capacitor banks being connected to the selected node buses. The analysis was focused on two monitored lines which were between 684 and 611 node bus, marked as line 684611 and also between 692 and 675 node bus, marked as line 692675. All the output results were discussed more details in the next subsection with clearer numeric figures in provided tables.

As for the harmonic current distortion, Figure 3 until Figure 4 showed the percentage of THDi for both monitored lines, before and after the capacitor banks being connected to the network system. It can be observed that the injection of the harmonic current spectrums has already caused the both line 684611 and line 692675 to violate the standard limit even right before the capacitor banks being activated into the system. Then by activated the operation of the capacitor banks, the distortion was transited to some value differently in each phases.
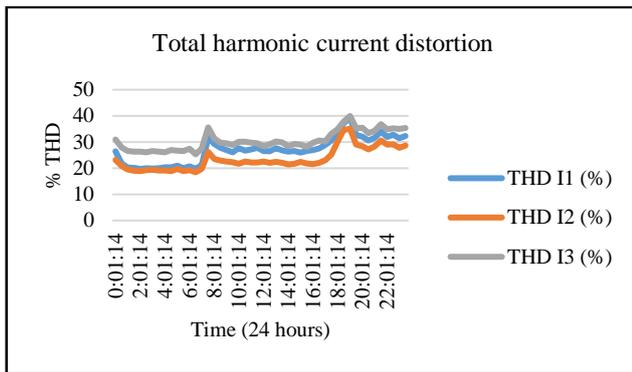
Figure 3. (a) THDi at line 692675 (without caps)   (b) THDi at line 692675 (with caps)
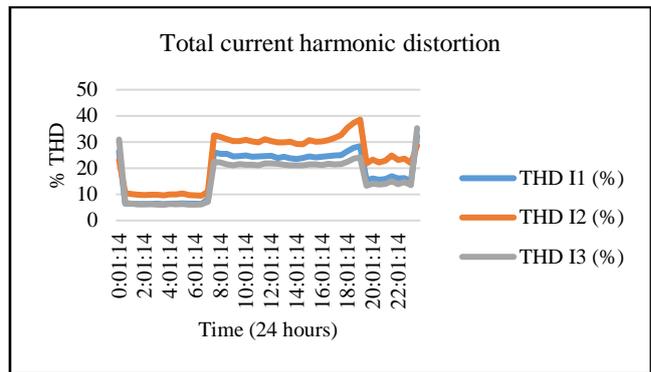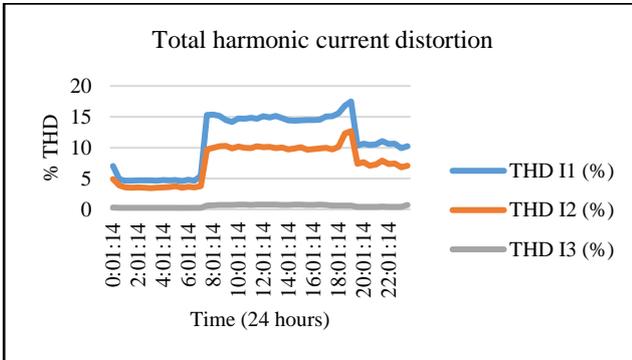
Figure 4. (a) THDi at line 684611 (without caps)   (b) THDi at line 684611 (with caps)
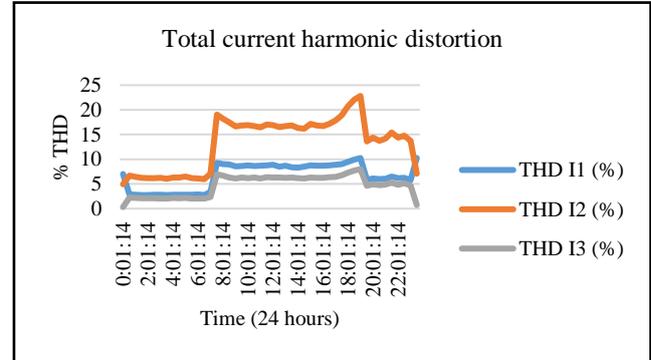
Meanwhile, Figure 5 until Figure 6 showed the simulation graph results of THDv for both monitored lines before and after the capacitor banks being connected to the network test system. From all figures, it clearly observed that harmonic voltage distortions were transited and magnified in all phases.
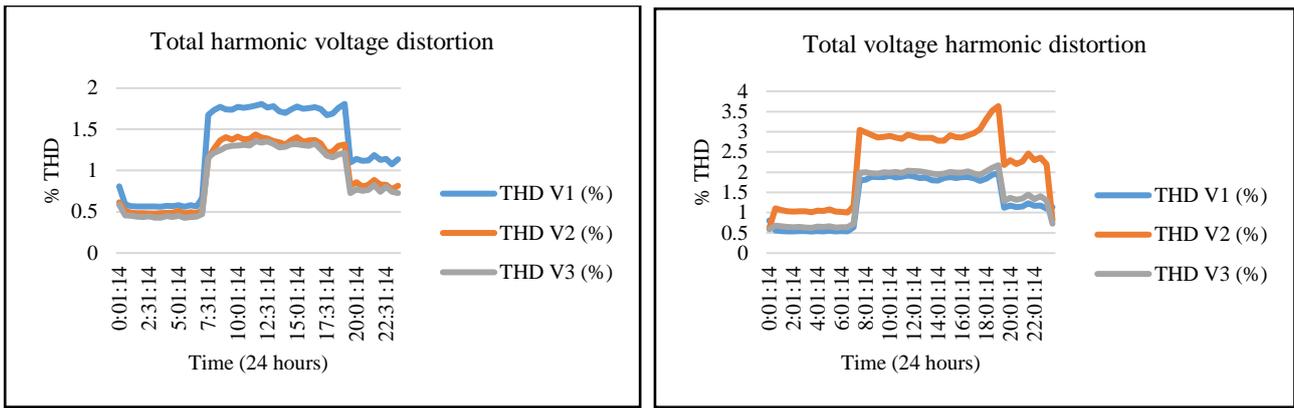
Figure 5. (a) THDv at line 692675 (without caps)   (b) THDv at line 692675 (with caps)
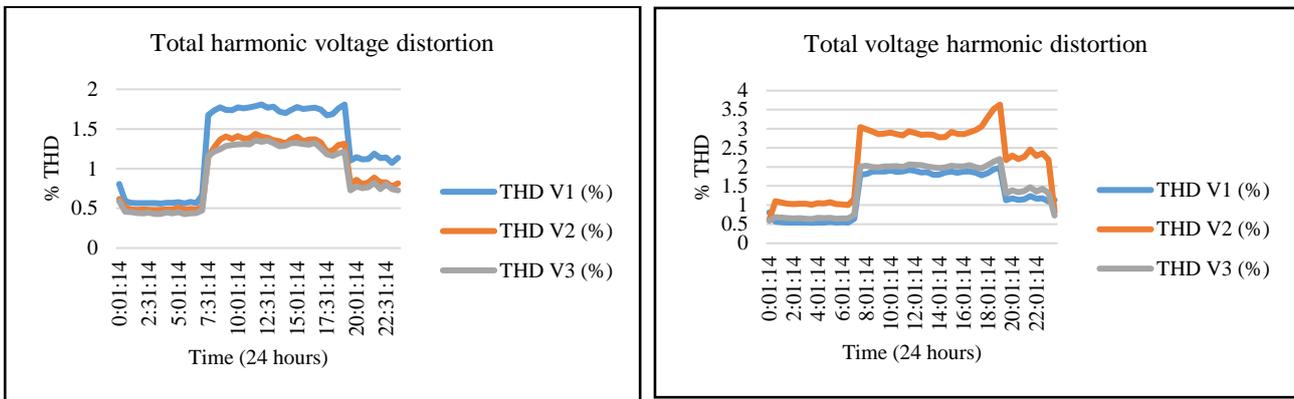
Figure 6. (a) THDv at line 684611 (without caps)   (b) THDv at line 684611 (with caps)

The simulation graphs result in above figures showed that the monitored lines were having significant differences in the THDi and THDv values, before and after the distribution capacitors being connected to the network system. The harmonics contents which were already existed in the network seem to be actively mushroomed and instantly increased the THDi (in certain phases) and THDv (in all phases).

The exact numeric figures to show the changes of the percentage THD value can be best observed in the Table 5 and Table 6 for both monitored lines. The transistion in THDi level from the Table 5 has revealed the effect of the resonance from the capacitors operation which has increased the THDi but only in certain phases. The highest increment was happened at second phase of line 684611 which was almost up to two times higher from its initial level. It must be noted that, with such high THD level, the overall network system could be seriously jeopardized. At this point, if the resonant is the same as the harmonic component, unpredicted burn out of the system's equipment or devices may occur due to the amplified harmonic current [12].

An improvement in the future work should be done in order to analyse the nonuniformity increment in the THDi. As for this case study, the assumption for the nonunifomity was due to the value of impedance from load and supply in between the lines has somehow caused the THD to decreased [14]. This condition is actually can determine the responsibility of the excessive THD either it is the utility side or the customer side, but it will not be discussed in this paper.

Table 5. The percentage of THDi without and with distribution capacitors

Monitored line	Percentage of THDi (without caps)	Percentage THDi (with caps)
684611	i_1= 17.4800 % i_2= 12.6835 % i_3= 0.7174 %	i_1= 10.2508 % i_2= 22.8175 % i_3= 7.9802 %
692675	i_1= 39.2775 % i_2= 35.0859 % i_3= 39.9679 %	i_1= 32.2898 % i_2= 38.5694 % i_3= 35.3215%

The THDv on the other hand, the changes in the increment of distortion percentage values were experienced by all phases. But the percentage values of the THDv were seem not too high and still under compliance of 5% for the 2.4kV distribution system standard. But despite to that, it must be taken into precaution action as to avoid the unwanted even such as sudden breakdown or failure which could brought into huge loss in the network system.

Table 6. The percentage of THDv without and with distribution capacitors

Monitored line	Percentage of THDv (without caps)	Percentage THDv (with caps)
684611	v_1= 1.8065 % v_2= 1.4352 % v_3= 1.3557 %	v_1= 1.9769 % v_2= 3.6327 % v_3= 3.2079 %
692675	v_1= 1.8084 % v_2= 1.4386 % v_3= 1.3565%	v_1= 1.9786 % v_2= 3.6330 % v_3= 2.1742 %

Other than that, it is important to determine which harmonic order when all the excessive THD occurred. This is because they will indicate either it could jeopardize the network system or not. Theoretically, only odd harmonic order could harm the system and shall not be worried if the resonance occurred during aneven harmonic order. Based on the harmonic order acquired from the resonance frequency for this research work, the results obtained which illustrated in the Table 7 below shall not be much concerned because they were not in significant odd order. But still, it can be said that the resonance frequency from the capacitor banks did played a very important role in harmonic and distortion occurrence.

Table 7. The resonance frequency and harmonic order at each node buses

Node	Resonance frequency, fr	Harmonic order, H
675 a	100.75 Hz	$1.42 \approx 1$
675 b	54.23 Hz	$1.08 \approx 1$
675 c	58.94 Hz	$1.18 \approx 1$
611	79.47 Hz	$1.59 \approx 2$

4.0 CONCLUSION

In a conclusion, the hypothesis that the operation of the capacitor banks could give impact to the level of THD was clearly proven. In this case study, the real data of harmonic current injection from the commercial site has increased the existed THD at the monitored lines up to two times from the original reading and this could be hazardous to the network system. Anyhow, the case study in this paper showed that the THD increment still could not affect the stability of the network system as it happened on insignificant harmonic order, but it is still must be put into precaution zone in order to avoid the unexpected failure that can cause massive loss for the network. Hence, a proper monitoring and maintenance system shoud be provided and perhaps it will continuously benefit all related parties either from supply or from the loads.

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