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A Norton Model of a Distribution Network for Harmonic Evaluation

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Abstract
This paper presents a Norton model for modelling distribution networks where the system configuration is not fully known. Traditionally harmonic studies use complex distribution networks modelled by harmonic current sources for specific frequencies. Although this model has been proved to be adequate for some studies, this may not be adequate for other applications. When changing the operating conditions of the supply-side system, the harmonic currents injected by the distribution network might change and to investigate these harmonic currents, the Norton model is used. The change of operating condition is obtained by switching shunt capacitors. The estimated model can be used to analyze, for example, the effect of harmonic filters under different supply system configurations or operating conditions. The method of estimating the Norton models is illustrated on a test system, simulated on the well-known simulation program EMTP-ATPDraw.

Key words: Norton model; Distribution network; Operating conditions; Harmonic currents and voltages

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Nomenclature

EMTP	Electromagnetic Transient Program	Rho	Earth resistance [Ω]
ATP	Alternative Transient Program	C	Capacitance [F]
I_h	Harmonic current	P	Active power [W]
V_h	Harmonic voltage	Q	Reactive power [VAr]
$I_{ZN,h}$	Harmonic Norton current	ΔT	Time step of simulation [s]
$Z_{N,h}$	Harmonic Norton impedance	Tmax	End time of simulation [s]
R	Resistance	Xopt	Inductances in [mH]
L	Inductance	Copt	Capacitances in [μF]
Z	Impedance	Freq.	System frequency in [Hz]
X	Reactance	FFT	Fast Fourier Transform
V_{rp}	Primary voltage	THD	Total harmonic deformation
V_{rs}	Secondary voltage		

INTRODUCTION
The use of power electronics-based devices in power systems has increased steadily over the last decades. Electronics devices are nonlinear and thus they create distorted currents even when supplied with purely sinusoidal voltage. These distorted currents cause voltage and current distortion throughout the system which can result in additional heating in power system equipment, unmotivated switching of breakers, blowing of fuses, and interference with communication systems[1]. Microprocessor based controls applied in these electronics devices are sensitive to many types of disturbances which can result in nuisance tripping, misoperation or actual

device failures.

Generally the distribution systems consists of several shunt connected impedances. In all power systems capacitors are used for power factor correction and they change the system frequency characteristics which can result in resonances that magnify specific harmonic voltages and transient disturbances. Changing the operating condition of the supply system might change the harmonic currents injected at the measured bus. The characteristics of many distribution networks suggest that for distribution networks, the Norton approach would be more suitable, since the common harmonic generating loads in distribution networks often have the characteristics of harmonic current sources. Thus, to estimate a harmonic Norton model of a distribution network as given in Figure 1, measurements of harmonic current (I_h) and voltage (V_h) for, at least, two different operating conditions of the supply system have to be performed[2].

The purpose of this paper is to show how to estimate a Norton model of a distribution system from harmonic voltage and current measurements. The change in supply system operating condition can for example be obtained by switching a shunt capacitor, disconnecting a parallel transformer or some other changes that give a significant change in the supply system harmonic impedance. It is however required that voltage and current can be measured, or estimated, on both sides of the device that are being switched.

Through the circuit in Figure 1 it can be seen that by changing the operating conditions of the supply system (at least two changes), then harmonic voltage (V_h) and harmonic currents (I_h) and ($I_{ZN,h}$) will be changed.

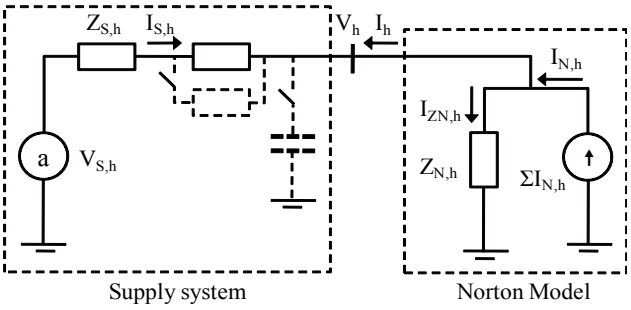

Figure 1
Norton Model of a Distribution Network

Assuming no change in operating conditions in the modeled load-side distribution network between the two measurements, it is seen from Figure 1 that for each harmonic, the measured currents ($I_{h,1}$) and ($I_{h,2}$) can be expressed as[2, 3, 4, 5]:

$$I_{h,1}=I_{N,h}-I_{ZN,h,1} \quad (1)$$

$$I_{h,2}=I_{N,h}-I_{ZN,h,2} \quad (2)$$

$$I_{ZN,h,1}=\frac{V_{h,1}}{Z_{N,h}} \text{ and } I_{ZN,h,2}=\frac{V_{h,2}}{Z_{N,h}} \quad (3)$$

Where $Z_{N,h}$ is the harmonic Norton impedance.
Using equation (3) in equation (1) and (2) gives:

$$I_{h,1}=I_{N,h}-\frac{V_{h,1}}{Z_{N,h}} \text{ and } I_{h,2}=I_{N,h}-\frac{V_{h,2}}{Z_{N,h}} \quad (4)$$

Subtracting ($I_{h,1}$) from ($I_{h,2}$) gives:

$$I_{h,2}-I_{h,1}=\frac{V_{h,1}-V_{h,2}}{Z_{N,h}} \quad (5)$$

The Norton impedance for each harmonic is:

$$Z_{N,h}=\frac{V_{h,1}-V_{h,2}}{I_{h,2}-I_{h,1}} \quad (6)$$

The harmonic Norton current source can then be calculated as:

$$I_{N,h}=I_{h,1}+\frac{V_{h,1}}{Z_{N,h}} \quad (7)$$

From equations (6) and (7) it is seen that all information needed for the calculations of the harmonic Norton model can be found in the two measurements of harmonic voltage and current. No information about the supply system harmonic impedance or the modeled load-side network is needed.

The equations (6) and (7) are complex, it is important to have correct measurements of not only the harmonic voltage and current magnitudes but also the phase angles.

To illustrate the method of estimating the Norton model and to show the performance of the estimated models, the method was tested on a simple power system shown in Figure 2. This system was simulated on the EMTP-ATPDraw v5.7p2[6].

1. CIRCUIT DESCRIPTION

The system corresponds to a distribution network fed by 22 kV network via a transmission line 1, 10 km long and made of AlFe6-70 mm^2. The substation T1 transform the voltage down to 6 kV, which feeds the distribution transformers 6/0.4 kV. The harmonic loads at buses 10 and 11 inject 5th, and 7th harmonic currents into the system.

Switching of the capacitor banks (2×10 MVAr), connected to bus 3, will provide the two different operating conditions, needed for the estimation of the Norton model. It is important to note that the switching events must produce significant change in current and voltage, in which V_h and I_h are not zeroes. These conditions do not enable the impedance to be calculated. Therefore, only switching test, which produce significant change in harmonic voltage and current, is presented in this paper. The capacitors which use for the power factor correction in power systems are suitable to be used for this operation.

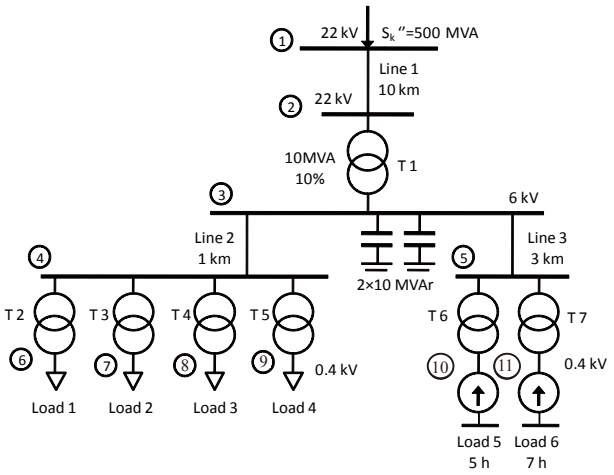

Figure 2
Simulated Test System

2. MODEL CONSTRUCTION

1.1 22 kV Network

The network was modelled by the ATP model AC3PH-type 14, constant voltage with amplitude equals to ($22 \times \sqrt{2}/\sqrt{3}$ = 17.96 KV) and internal impedance (R=0.09Ω, L= 2.866 mH).

1.2 Transformers

All transformers are modelled by SATTRAFO (Δ-Y, with ground Y). The values of R and L are taken to the secondary side of the transformer and use the common X/R ratio for transformers as 10[7]. First we calculate the impedance from the secondary voltage and the power ($Z=V^2/P$), then we take the percentage value of Z (for example 10% for transformer 1). This result represents the magnitude of Z, or $|R+jX|$. and from (X/R=10) and the equation ($Z=\sqrt{R^2+X^2}$)[8] we calculate that R and L (XL=jωL).

The primary voltage is(Δ)Therefore, the peak primary rated voltage (Vrp=√2×V) and the secondary voltage is (Y), so the peak (Vrs=√(2/3)×V)[9]. All calculations are listed in the table below.

Table 1
The Parameters of the Transformers

Transformer	V_{rp} (kV)	V_{rs} (kV)	R (Ω)	L (mH)
T1 (22kV/6kV), 10MVA 10% impedance	31.113	4.899	0.036	1.14
T2 and T3 (6kV/400V), 750kVA 4% impedance	8.485	0.327	0.001	0.027
T4 and T5 (6kV/400V), 1MVA 4% impedance	8.485	0.327	0.001	0.0203
T4 and T5 (6kV/400V), 2.5MVA 6% impedance	8.485	0.327	0.0004	0.0122

1.3 Transmission Lines

All transmission lines are modeled by the ATP model LCC Lines/Cables as an overhead lines, type PI-Model. Rho=100 Ω, Freq. init = 50 Hz. The 22 kV line 1 is made of AlFe6-70 mm^2, The 6 kV line 2 and 3 are made of AlFe6-35 mm^2. The parameters are in Table 2.

Table 2
Parameters of the Transmission Lines

Line	length (km)	React (Ω/km)	Rout (cm)	Resis (Ω/km)	Horiz (m)	Vtower (m)	Vmid (m)
1	10	0.431	0.57	0.432	0.75	10.5	9.5
2	3	0.428	0.42	0.778	0.75	10.5	9.5
3	5	0.428	0.42	0.778	0.75	10.5	9.5

3.4 Loads

All loads are modelled by the ATP model RLC_3, where the values of the model are calculated by the equations [3] $R=U^2/P$, $L=(U^2/Q)/2\pi f$ and C=0. The values are listed in the table below.

Table 3
Parameters of the Loads

Load	P (kW)	Q (kVAr)	cos α	R (Ω)	L (mH)
1 and 2	300	264.575	0.75	0.481	1.738
3 and 4	500	375	0.8	0.289	1.226
5 and 6	1000	619.744	0.85	0.144	0.742

2.5 Capacitor Banks

The capacitor banks (2×10 MVAr) are modelled by the ATP model CAP_RS, where the value of a phase capacitor is calculated as $C=(Q/2\pi fU^2)=884.64$ μF, then 2×884.64≈1770 μF.

3. RESULTS AND DISCUSSION

Finally we have to set the simulation values of the ATPDraw as (ΔT=0.1μs, Tmax=2 s, Xopt=0, Copt=0 and Freq=50 Hz) and build the ATP model of the network as shown in Figure 3 below.

Our interest in this study will be to investigate the harmonic content of the current that flows from bus 3 to the bus 5 and the voltage at the bus 3. The simulations are carried out using the electromagnetically transient program EMTP-ATP [6, 11] and the graphs are drawn by the MC's PlotXWin. Fast Fourier Transform (FFT) is performed to discriminate harmonic components of the currents and voltages and their phase angles needed for the calculation of the Norton model as described in equations (6) and (7).

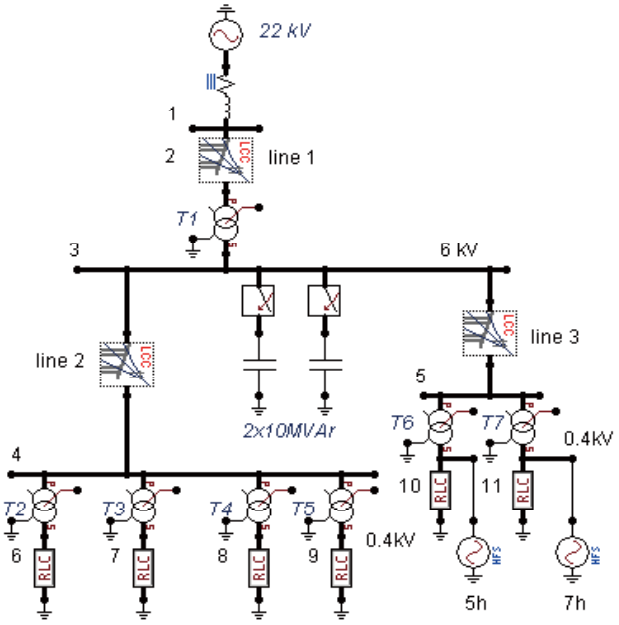

Figure 3
The Network ATPDraw Model

3.1 Before the Disconnection of Capacitors

The current which flows from the bus 3 to the bus 5 contains the 5th and the 7th harmonics and it is shown in Figure 4 below and the harmonics spectra of this current is shown in Figure 5. The values of the harmonic contents are listed in Table 4 below for the magnitude and the phase shift.

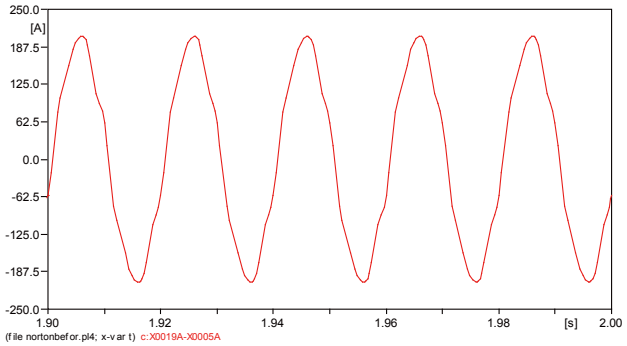

Figure 4
The Wave Form of the Current

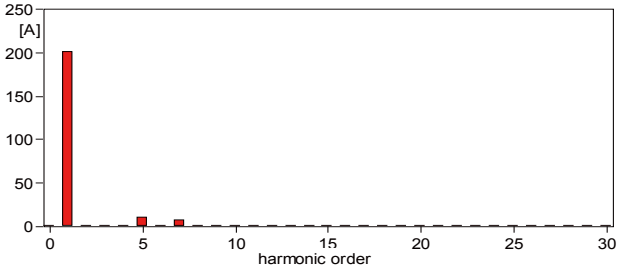

Figure 5
The Harmonics Spectra

Table 4
The Harmonic Current Between Bus 3 and 5

h	Magn. (A)	Phase (°)	h	Magn. (A)	Phase (°)	h	Magn. (A)	Phase (°)
1	200.86	-5.01	11	0.002	-13.98	21	0.001	10.68
2	0.013	8.78	12	0.002	-9.61	22	0.001	12.22
3	0.008	22.02	13	0.002	-6.12	23	0.001	13.71
4	0.006	43.71	14	0.001	-3.19	24	0.001	15.15
5	10.506	-82.54	15	0.001	-0.64	25	0.001	16.55
6	0.003	12.44	16	0.001	1.63	26	0.001	17.92
7	7.006	-80.95	17	0.001	3.69	27	0.001	19.26
8	0.004	-44.10	18	0.001	5.60	28	0.001	20.57
9	0.003	-28.59	19	0.001	7.38	29	0.001	21.86
10	0.002	-19.85	20	0.001	9.07	30	0.001	23.14

THD = 6.2867 %

The wave form oh the voltage at bus 3 is shown in Figure 6 and the harmonics spectra is shown in Figure 7. The values of the harmonic contents are listed in Table 5.

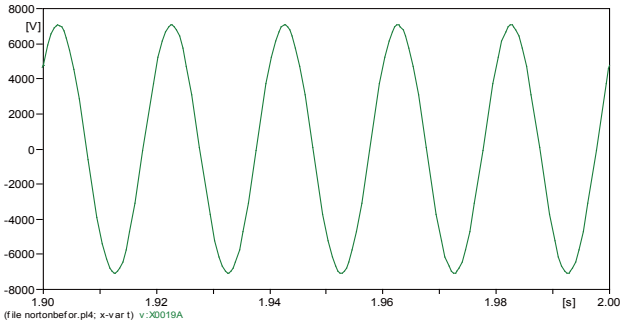

Figure 6
The Wave Form of the Voltage

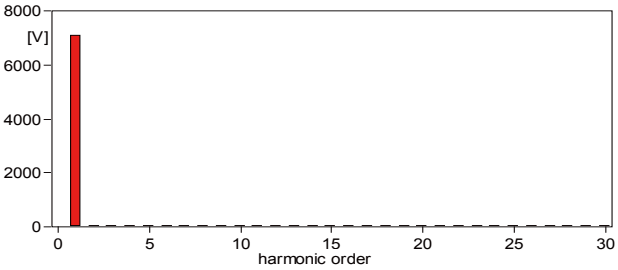

Figure 7
The Harmonics Spectra

Table 5
The Harmonic Voltage at Bus 3

h	Magn. (V)	Phase (°)	h	Magn. (V)	Phase (°)	h	Magn. (V)	Phase (°)
1	7071.100	49.24	11	0.048	15.66	21	0.025	21.93
2	0.382	31.16	12	0.044	16.08	22	0.024	22.69
3	0.204	23.31	13	0.041	16.58	23	0.023	23.46
4	0.141	19.46	14	0.038	17.14	24	0.022	24.25
5	4.336	12.96	15	0.035	17.74	25	0.021	25.04
6	0.091	15.93	16	0.033	18.37	26	0.020	25.84
7	1.980	13.07	17	0.031	19.04	27	0.019	26.65
8	0.068	15.02	18	0.029	19.73	28	0.019	27.46
9	0.060	15.10	19	0.028	20.44	29	0.018	28.29
10	0.053	15.32	20	0.026	21.18	30	0.018	29.11

THD = 0.06778 %

3.2 After the Disconnection of Capacitors

For better illustration of this situation the disconnection time will be set at 1.95s, where the two different operating conditions are clearly seen in the figures below. The current which flows from the bus 3 to the bus 5 is shown in Figure 8 and the harmonics spectra of this current is shown in Figure 9. The values of the harmonic contents are listed in Table 6 below for the magnitude and the phase shift, where is clearly seen that the 5th and 7th harmonics have significant values.

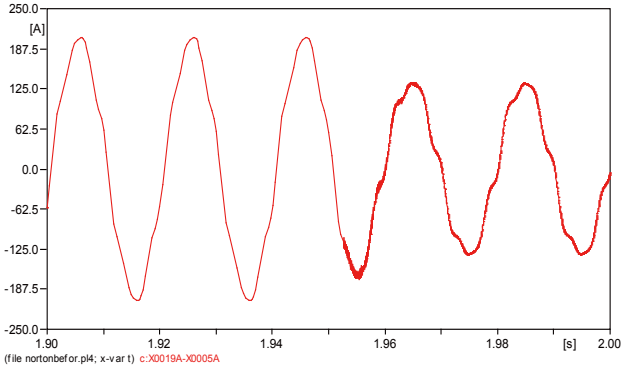

Figure 8
The Wave Form of the Current

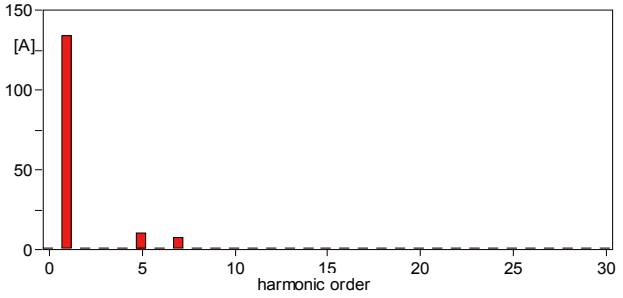

Figure 9
The Harmonics Spectra

Table 6
The Harmonic Current Between Bus 3 and 5

h	Magn. (A)	Phase (°)	h	Magn. (A)	Phase (°)	h	Magn. (A)	Phase (°)
1	133.40	5.70	11	0.001	-20.61	21	0.001	5.02
2	0.009	16.55	12	0.001	-15.90	22	0.001	6.49
3	0.006	30.17	13	0.001	-12.14	23	0.001	7.90
4	0.005	52.32	14	0.001	-9.03	24	0.001	9.25
5	10.242	-83.05	15	0.001	-6.35	25	0.001	10.55
6	0.002	15.58	16	0.001	-4.00	26	0.001	11.80
7	6.841	-81.45	17	0.001	-1.89	27	0.001	13.02
8	0.003	-50.99	18	0.001	0.03	28	0.000	14.20
9	0.002	-36.01	19	0.001	1.80	29	0.000	15.35
10	0.002	-26.90	20	0.001	3.46	30	0.000	16.48

THD = 9.2333 %

The wave form oh the voltage at bus 3 is shown in Figure 10 and the harmonics spectra is shown in Figure 11. The values of the harmonic contents are listed in Table 7.

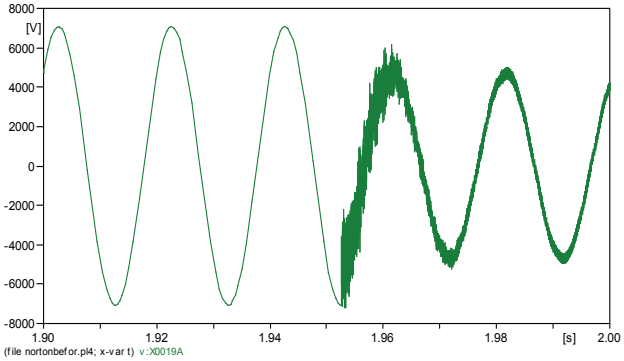

Figure 10
The Wave Form of the Voltage

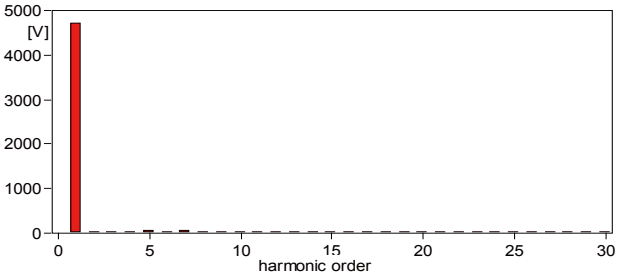

Figure 11
The Harmonics Spectra

Table 7
The Harmonic Voltage at Bus 3

h	Magn. (V)	Phase (°)	h	Magn. (V)	Phase (°)	h	Magn. (V)	Phase (°)
1	4696.2	60.35	11	0.017	28.55	21	0.009	36.78
2	0.210	41.88	12	0.016	28.65	22	0.009	38.00
3	0.107	31.40	13	0.015	29.06	23	0.009	39.25
4	0.078	24.05	14	0.014	29.69	24	0.008	40.53
5	34.473	174.86	15	0.013	30.46	25	0.008	41.84
6	0.043	22.87	16	0.012	31.34	26	0.008	43.17
7	32.185	-179.82	17	0.011	32.31	27	0.007	44.52
8	0.017	38.62	18	0.011	33.35	28	0.007	45.89
9	0.019	30.83	19	0.010	34.45	29	0.007	47.29
10	0.018	29.03	20	0.010	35.59	30	0.007	48.70

THD = 1.0473 %

From these results we can now calculate the Norton model currents and impedance according to the equations (6) and (7) described previously, but it is important to take into consideration, that the calculations are complex[6]. The calculations of the currents and voltages before and after the disconnection of the capacitors were carried for the harmonic orders from 1 up to 30, but for the estimated Norton model currents and impedance the results are for the main odd harmonics as listed in Tables 8 and 9. The figures 12 and 13 show the Norton impedance and the phase angles.

Table 8
Estimated Norton Model Currents

h	I (A)	Phase (°)
3	0.003	39.00
5	10.48	-82.64
7	6.997	-80.99
9	0.002	-43.21
11	0.001	-30.35
13	0.001	-22.80
15	0.001	-17.59
17	0.001	-13.64
19	0.001	-10.44

Table 9
Estimated Norton Model Impedance

h	Z (Ω)	|Z| (Ω)	Phase (°)
3	-43.787-10.665	45.067	193.69
5	-67.783-120.567	138.314	-119.34
7	-91.300-171.431	194.227	-118.04
9	-58.966-14.066	60.620	-166.58
11	-54.797-6.200	55.147	186.46
13	-53.475-1.843	53.507	181.97
15	-52.767+1.353	52.784	178.53
17	-52.262+3.989	52.414	175.64
19	-51.827+6.311	52.210	173.06

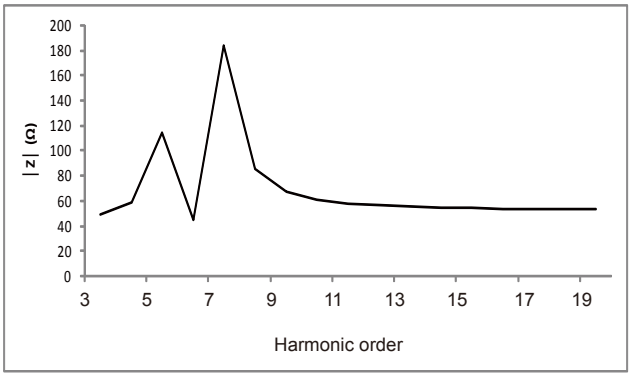

Figure 12
Estimated Norton Impedance

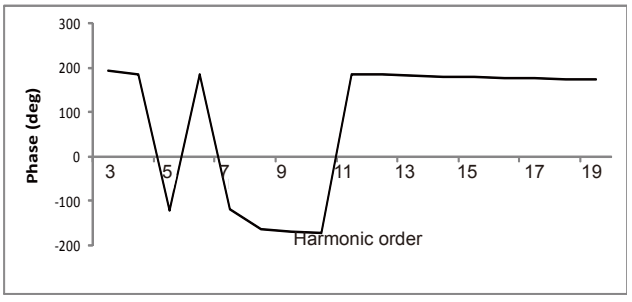

Figure 13
Estimated Norton Impedance Phase Angle

CONCLUSION

The main purpose of estimating the Norton model is that it can provide a simple and easily obtained model of distribution networks for the inclusion in harmonic load flow calculations. The information obtained from the measurements is typically the harmonic voltages and currents at the measurement location for different operating conditions, this process forms the data, which are needed for the calculation of the Norton model. Switching capacitor banks, in our case it was done by 2×10 MVAr, is equivalent to cause a transient short-circuit, resulting in a voltage and current in which the FFT gives their harmonic spectra.

Using harmonic measurements for, at least, two different operating conditions of the supply system it is possible to estimate not only the harmonic impedance but also a harmonic Norton model of a distribution network. To obtain useful Norton models for each harmonic it is important that the operating condition of the modeled distribution network does not change between the measurements.

From the obtaining data of the measured currents and voltages we can estimate the equivalent background har¬monic content of the current source. Table 8 gives us a clear scan about the harmonic content of the source current, were are seen the 5 th and the 7 th harmonics with the values 10.48 A and 6.997 A, respectively, while the rest of the harmonics have values close to zero, which proves the possibilities of using the Norton model for such study.

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