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Implementation of Fast Fourier Transformation in Detection of Several Flicker Sources

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ABSTRACT

Detection of flicker sources is the first step to mitigate the effect of flicker in power system. In this paper, in order to reduce the number of measurement devices, instantaneous voltages are estimated by using state estimation methods and then root mean square of the voltages and currents variation are detected and then signs of flicker powers are obtained in selected branches. By comparing the sign of flicker power with direction of fundamental active power, the place of flicker source is obtained. Unlike other methods, which could find only dominate flicker source, in this literature, existence of multiple flicker sources is studied and new algorithm for identifying of all flicker sources is presented. For validation, the 6-bus non-radial network is simulated and an algorithm for flicker sources detection is tested in this paper. The simulations results show that by using the proposed algorithm, all flicker sources in a non-radial network can be detected correctly.

KEYWORDS: FFT (Fast Fourier Transformation), Flicker Power, Flicker Sources, Power Quality, Sub-harmonic.

I. INTRODUCTION

In recent years, by Proliferation of non linear load in power network, power quality became of great importance for both consumers and utilities. One of the most important power quality events is flicker. Flicker defined as perception of the human eyes to the light flux of lamps which depend on voltage RMS value. According to IEC standard, flicker is defined as voltage fluctuation with frequency of 0.5-35 Hz [1]. Due to competition in power market, it is necessary to eliminate or reduce negative effects of flicker. Detection of flicker source's place is the first step to mitigate flicker in power system. After this stage by using the appropriate instrument or improving the network structure, flicker is mitigated.

Since now, many different methods for detection of flicker sources places have been presented. In one of them, with determining the slop of V-I characteristic, the place of flicker source is determined in observation point [2]. Another method is proposed for determining the direction of a flicker source by calculating the sign of the flicker power [3], [4]. Detection of flicker source in multi side supplied network has been considered in [5], and intelligent identification of flicker source is proposed by using S-transform and neural network in [6]. Generally in these methods only dominate flicker source is considered, while existence of multiple flicker sources in a power system is more realistic than single source. Another drawback of these methods is that they are mostly valid for radial network.

In this paper, by modifying the definition of upstream and downstream, they are generalized to non-radial network. State estimation is used to generate the best estimation of the state variables from limited measurements that are companied with measurement noise [7]. Due to the fact that in practice in a network, measurement of currents is easier than measurement of voltage [7], all bus voltages have been estimated by using state estimation. To detect multiple flicker sources in a non-radial power system, first bus voltages are estimated by using state estimation. Then envelope of voltages and currents are extracted and flicker power is calculated by using Discrete Fourier Transform (DFT). In the next step sign of flicker power in every line is specified and by using them, the places of flicker source are detected.

II. INSTANTANEOUS STATE ESTIMATION

For determination of the place of flicker sources in N-bus power network, minimum number of measurements is necessary that cause network become observable. There are N lines that flicker power should be analyzed in them and two possible choices are available. The first one is using power quality meter (PQ meter) in any selected line which is expensive and impractical for a large system. The second choice is using available measurement devices in network which is available in the control center. So in general, N currents and N voltages are needed. In real network, by using current measurements and relationships which exist in network, voltages can be calculated. Since measurements corrupt with noise, state estimation is used to generate the best estimation of all buses voltages from limited measurements of line currents or voltages [7]. The main equation of state estimation is given as:

$$z = h(x) + \varepsilon \tag{1}$$

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where z and x are measurements and state variables respectively, and ε is the measurement error. The function h relates the measured signals to system state variables and is depended on network structure. There are several performance criteria, but the most widely method is Weighted Least Square Method (WLSM) [7] that computed as (2).

$$J(x) = \frac{1}{2}[z - h(x)]^T R^{-1}[z - h(x)] \tag{2}$$

Then the vector x_{est} has been estimated by minimizing the weighted sum of the squares of the residual $\left(z - h(x)\right)$ as given in (3).

$$x_{est} = \arg\min_x J(x) \tag{3}$$

If line currents and some bus voltages are chosen as measurements (z), equation (1) becomes linear.

$$z = Hx + \varepsilon \tag{4}$$

If branch model is considered as PI model, Arrays of H are determined as follow:

$$H(k,i) = \frac{2C_{ij}}{\Delta t(1+\alpha)} + \frac{1+\alpha}{\frac{2L_{ij}}{\Delta t} + (1+\alpha)R_{ij}} \tag{5}$$

$$H(k,j) = -\frac{1+\alpha}{\frac{2L_{ij}}{\Delta t} + (1+\alpha)R_{ij}} \tag{6}$$

where α is a constant between 0 and 1, referred to be the compensating factor. R_{ij}, L_{ij} and C_{ij} are resistance, inductance and capacitance of branch *K* respectively, which is located between buses i and j, and Δt is sampling time [7]. Instantaneous bus voltages are then calculated as:

$$x_{est} = [H^T R^{-1} H]^{-1} H^T R^{-1} z_{meas} \tag{7}$$

where R is diagonal matrix and its arrows are the measurements error.

III. ENVELOP SEPARATION

Modulated voltage and current signals are as follow:

$$u_{AM}(t) = (U_c + m_u(t))\cos(2\pi f_c t) \tag{8}$$

$$i_{AM}(t) = (I_c + m_i(t))\cos(2\pi f_c t) \tag{9}$$

where $m_u(t)$ and $m_i(t)$ are low frequency fluctuation generating from flicker source and f_c is fundamental carrier signals. Different envelope tracking methods have been used in previous literature like square demodulation, but disadvantage of square demodulation is that it produces additional low frequency components [4]. Since there is more than one sub-harmonic in envelope, demodulation method which is shown in Fig. 1 is used in this paper. The complete separation process is shown in Fig. 1 and step by step process is described. First, signal is fed to a half-wave rectifier; the output of half wave rectifier is [4]:

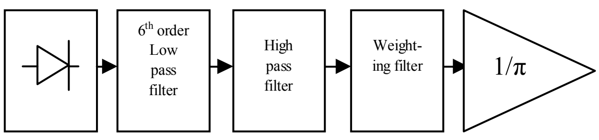

Fig. 1. Method of envelop separation

$$u_{AMrec}(t) = (U_0 + m_u(t)).\cos(\omega_c t)|_{rectifier}$$

(10)

Then is fed to a 6th order low-pass filter, so output signal from the rectifier and low-pass filter contains a dc component and a scaled version of the low frequency fluctuation as:

$$U_{de\bmod+lowpass-filter}(t) = \frac{1}{\pi}(U_0 + m_u(t))$$

(11)
After feeding to high-pass filter, weighting filter and then correction factor ($1/\pi$), envelope of signal is obtained. Filter chain is shown in Fig. 1 are described below:

The transfer function of the 6th order low-pass filter is defined as [8]

$$H_{lp} = \Pi_{i=1}^{3}(\frac{a_{0i} + a_{1i}z^{-1} + a_{2i}z^{-2}}{b_{0i} + b_{1i}z^{-1} + b_{2i}z^{-2}})$$

(12)
where $a_{ni}\,(n = 0,1,2)$ and $b_{ni}\,(n = 0,1,2)$ are digital filter coefficients. The transfer function of the high-pass filter is defined as (13).

$$H_{hp}(z) = \frac{a(1-z^{-1})}{1+bz^{-1}}$$

(13)
where a and b are constants which are:

$$a = 2\tau f_s/(1+2\tau f_s)$$
$$b = (1-2\tau f_s)/(1+2\tau f_s)$$

f_s, f_{hp} and τ represent sampling frequency, cut-off frequency and time constant respectively. The third filter is a weighting filter and its related equation is given in (14) [8].

$$H_{wf}(z) = (\frac{a_0 + a_1z^{-1} + a_2z^{-2} + a_3z^{-3}}{b_0 + b_1z^{-1} + b_2z^{-2} + b_3z^{-3} + b_4z^{-4}})$$

(14)
where $a_n\,(n = 0,1,2,3)$ and $b_n\,(n = 0,1,2,3)$ are digital filter coefficients.

IV. PROPOSED METHOD FOR DETECTION OF FLICKER SOURCES

The main purpose of this paper is the detection of flicker sources in a non-radial power network. In radial network, recognition of upstream and downstream is easy. Upstream is toward utility and downstream is toward load. But in non-radial system it is hard to recognize as each feeder is supplied from more than one side. In this case, fundamental power flow direction in any line under study should be determined and then upstream is in the opposite direction from fundamental power flow and downstream is in the same direction as fundamental power flow.

In this paper, novel method which is applicable to any network with multiple flicker sources is proposed. Due to the presence of some sub-harmonic, which mainly is related to different sources of flicker, DFT has been applied to voltages and currents envelopes to calculate power flicker and then all of flicker sources could be detected.

The block diagram of the proposed flowchart is shown in Fig. 2. Measured values of currents and base voltage in form of discrete data, which is created from simulated power system in PSCAD, have been used as input. In a real network these data can be collected from measurement devices. The proposed method has four parts and MATLAB has been used for simulation for these parts.

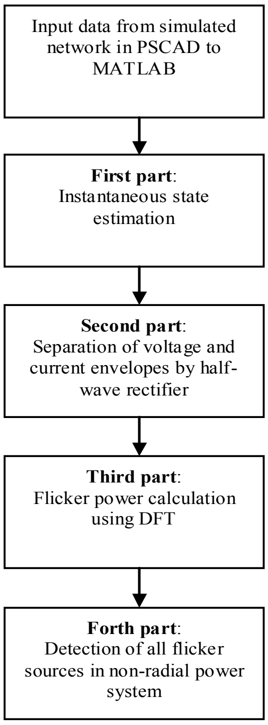

Fig. 2. Block diagram of the proposed method

First part: state estimation

In an N-bus power system, N measured currents and one measured voltage (base voltage), are used as input for state estimation. The complete process of this part is given in section II, where the outputs of this stage are the estimated voltages of network buses.

Second part: envelope separation

In this part, as it is possible to have more than one sub-harmonic, a demodulation method, as shown in Fig. 1, has been used. Inputs of this stage are measured currents and estimated voltages extracted from first part and outputs of this stage are voltages and currents envelopes. More detailed discussion of this part is given in section III.

Third part: flicker power calculation using DFT

In this part, tracked envelopes of voltages and currents extracted in previous stage pass to DFT and then by multiplying DFT of current envelope and DFT of voltage envelope, flicker power is calculated in any subharmonic.

$$U = [|U_1|\angle\beta_1, |U_2|\angle\beta_2, ...|U_N|\angle\beta_N]$$

(15)

$$I = [|I_1|\angle\alpha_1, |I_2|\angle\alpha_2, ...|I_N|\angle\alpha_N]$$

(16)

In (15) and (16), U and I are array of complex values showing the DFT of voltage and current envelopes. U_K and I_K' where K=1, 2,…, N are the orders of frequency derived by DFT analysis, are the voltage and current phasors of the subharmonics respectively. Therefore flickers power in any sub-harmonic can be expressed as:

$$S_k = U_k . I_k^* = P_k + jQ_k$$
$$P_k = real\{S_k\}$$

(17)

Fourth part: detection of all flicker sources in non-radial power system

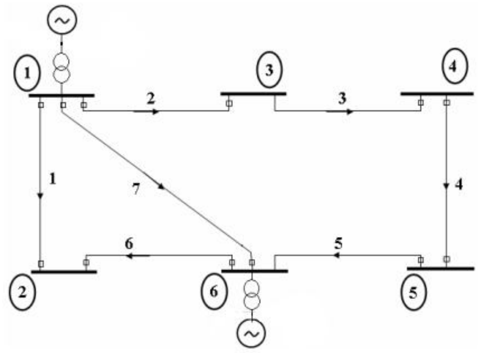

Fig. 3. Test system

In non-radial power system, upstream and downstream are defined with respect to fundamental power flow direction in any line. Fundamental power flow directions in each line are calculated using by measured currents and estimated voltages. Comparing fundamental power flow direction with power flickers in any sub-harmonic, places of all flicker sources are determined. If flicker power was positive, it implies that flicker source is upstream with respect to fundamental power flow direction and if flicker power was negative, it implies that flicker source is downstream with respect to fundamental power flow direction.

In real power system, system and load parameters may change with time, so it may be needed to run this algorithm periodically, e.g. in every ten minutes. It causes that flicker sources identification process is updated with respect to power system changes.

V. SIMULATION RESULTS

In this section simulations for different cases have been carried out to verify the effectiveness of the proposed algorithm in detecting the multiple flicker sources in non-radial network. The PSCAD software has been used to capture the instantaneous waveforms of the voltages and currents in test cases. Then these results have been used as input for MATLAB simulations to conduct.

Arc furnaces are one of the main loads which can produce flicker in the power network. There are some proposed models for the arc furnaces. Generally the performance of an arc furnace can be simulated by hysteric characteristic [10]. Therefore equations (18) and (19) have been used to simulate the non-linear characteristic of the arc furnace.

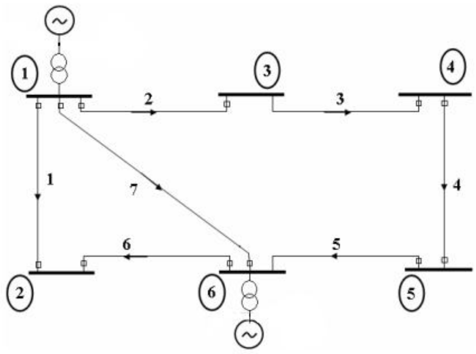

Fig. 3. Test system

$$k_1 r^n + k_2 r \frac{dr}{dt} = \frac{k_3}{r^{m+2}} i^2$$

(18)

$$v = \frac{k_3}{r^{m+2}} i$$

(19)

In (18) and (19), v , i , r , $k_i (i = 1,2,3)$ are arc voltage, arc current, arc length, and constant coefficient respectively and n, m are constants that are dependent on melting process. In this paper, arc furnace is modeled in PSCAD with the following parameters:

$$k_1 = 2700,\ k_2 = 1.0, k_3 = 12.5$$

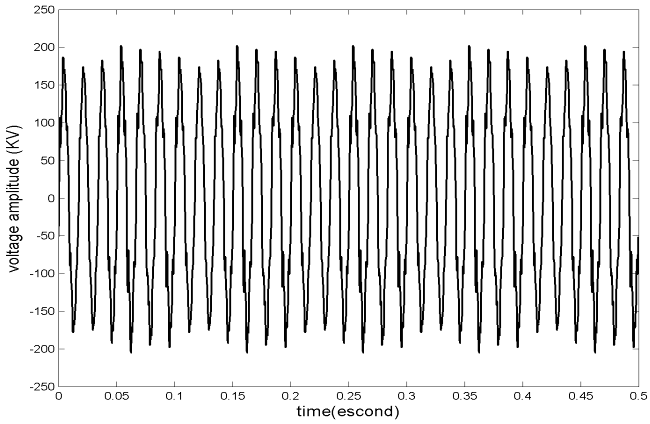

Fig. 4. Real voltage of bus 6

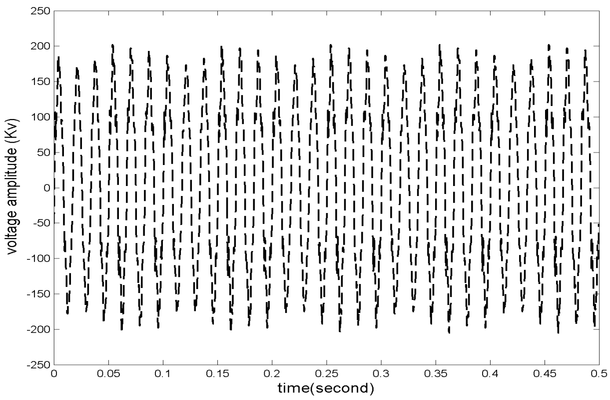

Fig. 5. Estimated voltage of Bus 6

Table. I. MAXIMUM ERRORS BETWEEN REAL AND ESTIMATED VALUES OF BUS VOLTAGE

Error\\voltage	Bus 2	Bus 3	Bus 4	Bus5	Bus 6
Error Max%	0.08	0.07	0.15	0.22	0.20

A simulation based on 6-bus test system is used to demonstrate the proposed approach. Fig. 3 shows a 220 KV power network which is supplied by two 11 KV generators and its data is given in APPEDIX [9]. In this study, two different cases are considered and analyzed. In the first case, the applicability of the proposed method for network with only one flicker source has been examined and in the second case; a network with two flicker sources has been considered.

Case I

In this section, only one arc furnace in power network connected to bus 5 has been considered. Envelope frequency is 10 Hz and amplitude modulation is 0.1 PU. Simulation results of all four parts of the proposed algorithm are given in the following sections.

Simulation result of the first part:

In this stage, voltages are estimated using instantanious state estimation, for exmaple the real voltage of bus 6 and its estimated waveformn are shown in Fig. 4 and Fig. 5 respectivly. Maximum errors for every estimated bus voltage are given in Table I. Theses results show that the estimated voltages are acceptable and therir maximum error is limited to about 0.22%.

Simulation result of the second part:

Block diagram shown in Fig. 1 is used for envelope separation. The constant values and coefficients of the 6th order low-pass filter, high pass filter, and weighting filter are given below. Envelopes of the voltages at Bus 6 and current in Line 6 are shown in Fig. 6 and Fig. 8 respectively.

$$a_{0i} = a_{1i}/2 = a_{2i} = (1 + cd_i + c^2)^{-1} \quad , \quad b_{0i} = 1$$

$$b_{1i} = 2a_{0i}(1 - c^2) \quad , \quad b_{2i} = a_{0i}(1 - cd_i + c^2)$$

$$c = 1/\tan(\pi f_{lp} / f_s) \quad , \quad d_1 = 1.93185165$$

$$d_2 = 1.41421356 \quad , \quad d_3 = 0.51763809$$

$$a_0 = 0.09487215 \quad , \quad a_1 = -0.1582865$$

$$a_2 = 0.04023729 \quad , \quad a_3 = 0.02317702$$

$$b_0 = 1 , \; b_1 = 3.167151 \quad , \quad b_2 = 3.752054$$

$$b_3 = 1.958255 \quad , \quad b_4 = 0.3747149$$

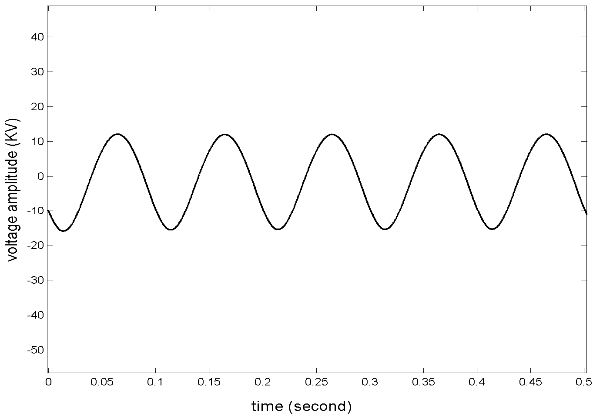

Fig. 6. Bus 6 voltage envelope

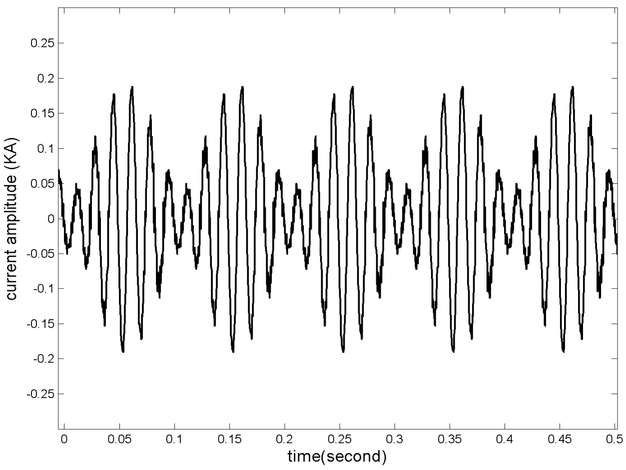

Fig. 7. Current in Line 6

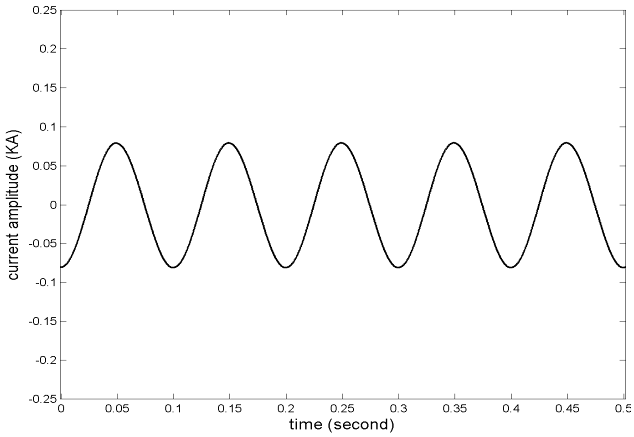

Fig. 8. Envelope of the current in Line 6

Simulation result of the third part:

Flicker power and fundamental active power are given in Table II. Fundamental power direction at any part of network is used as reference for flicker power sign. These sign of flicker power is used to decide whether flicker source is downstream or upstream with respect to point of study.

Simulation result of the fourth part:

Based on the values of the powers shown in Table II, direction of fundamental and flicker power flows are shown in Fig. 9. In this case, negative flicker power was expected at the two lines feeding the arc furnace, because the flicker source was located downstream with respect to fundamental power flow direction of these two incoming lines.

In Fig. 9, flat arrows represent direction of fundamental power flow and curved arrow represent power flicker. By following the direction of flicker power, the place of flicker source can be found. Thus, the load connected at bus 5 is a flicker source.

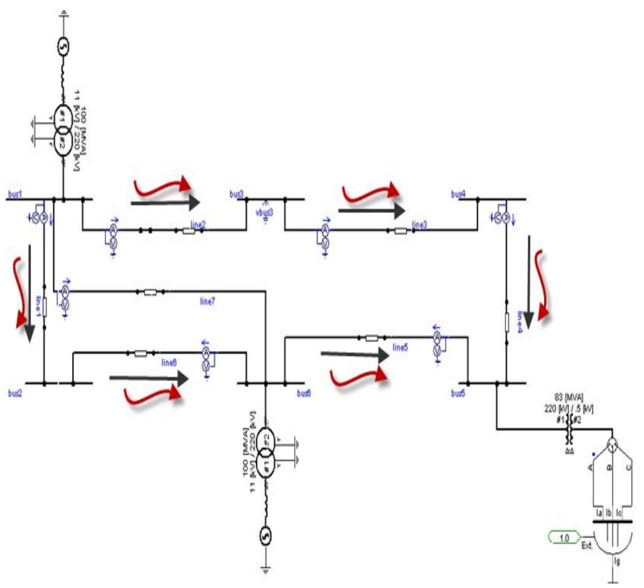
Fig. 9. Graphical simulation result of the first case

TABLE. II. SIMULATION RESULT OF FIRST CASE

Branch No.	Fundamental power (MW)	Flicker power (MW)	Sign of Flicker Power
1	+15.67	-0.147	*negative*
2	+52.72	-0.290	*negative*
3	+52.63	-0.295	*negative*
4	+52.53	-0.295	*negative*
5	+130.4	-0.730	*negative*
6	+15.48	-0.094	*negative*

Case II

In this case two flicker sources has been connected in network, first arc furnace is connected to bus 2 with envelope frequency of 10 Hz and amplitude modulation of 0.1 PU and the second arc furnace is connected to bus 5 with envelope frequency of 5 Hz and amplitude modulation of 0.07 PU. The proposed flicker source detection processes are detailed in the following parts.

Simulation result of the first part:

Similar to case I, In this stage, all voltages are estimated using instantanious state estimation, for exmaple the real voltage of bus 6 and its estimated waveformn are shown in Fig. 10 and Fig. 11 respectivly.

Simulation result of the second part:

Envelope of the voltage at Bus 6 and current in Line 6 are shown in Fig. 12 and Fig. 13 respectively.

Simulation result of the third part:

Flicker power and fundamental active power are given in Table III. Fundamental power direction at any part of network is used as reference for flicker power sign. These sign of flicker power is used to decide whether flicker source is downstream or upstream with respect to point of study.

Simulation result of forth part:

Based on the values of the powers shown in Table III, direction of fundamental and flicker power flows are shown in Fig. 14. In this figure, long curved arrow represents flicker power of subharmonic related to 5 Hz and short curved arrow represents flicker power of sub-harmonic related to 10 Hz, also dashed arrow are presented direction of fundamental power flow. By fol-

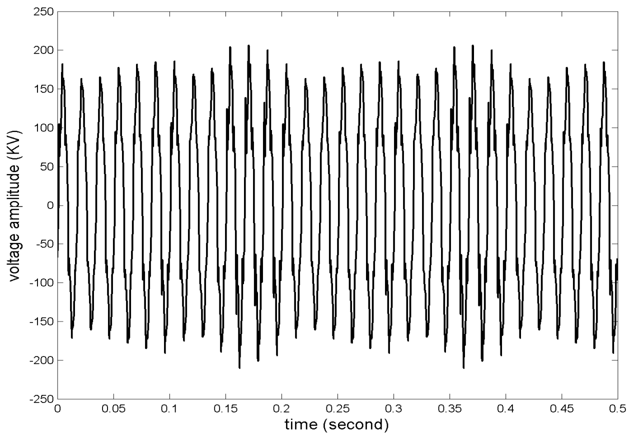

Fig. 10. Actual voltage at bus 6

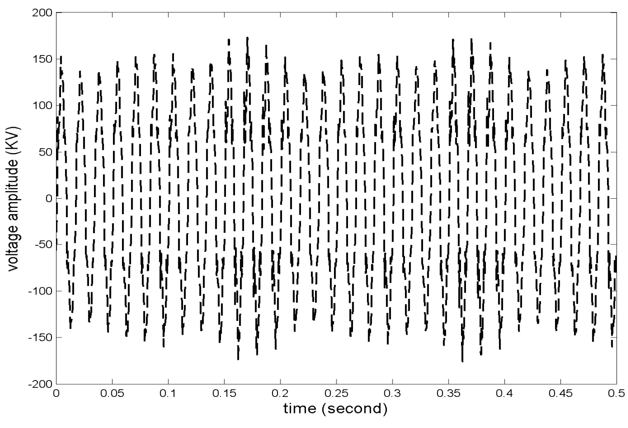

Fig. 11. Estimated voltage of bus 6

lowing the long curved arrow, bus 2 which is the place of arc furnace producing 10 Hz sub-harmonic, is achieved. In the same way by following short limber arrow, bus 5 which is the place of other arc furnace is determined.

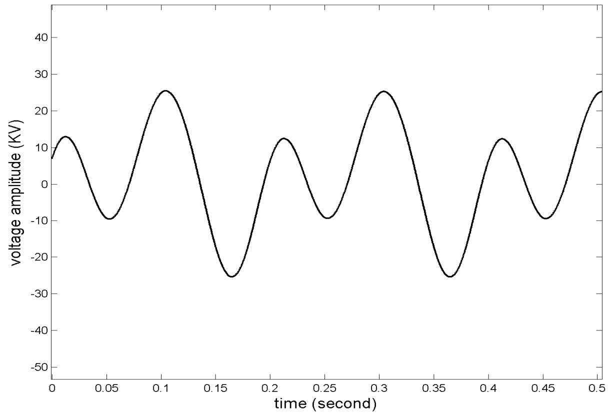

Fig. 12. Voltage envelope of bus 6

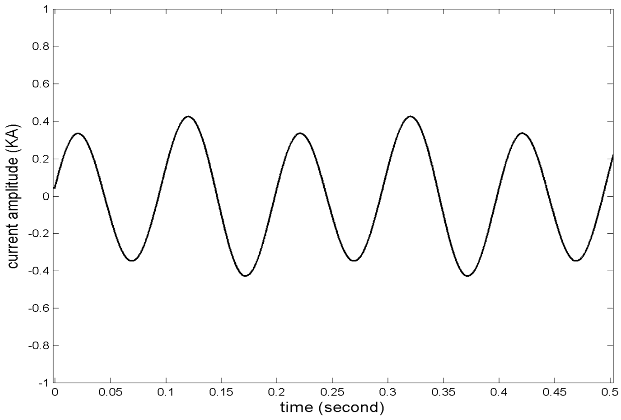

Fig. 13. Current envelope of line 6

Branch No.	*Fundamental power (MWatt)*	*Flicker power (MWatt) At f_1(10 Hz)*	*Sign of Flicker Power at f_1(10 Hz)*	*Flicker power (MWatt) At f_2(5 Hz)*	*Sign of Flicker Power at f_2(5 Hz)*
1	*92.11*	*-0.765*	*negative*	*+0.031*	*positive*
2	*58.82*	*+0.077*	*positive*	*-0.060*	*negative*
3	*58.62*	*+0.076*	*positive*	*-0.061*	*negative*
4	*58.41*	*+0.076*	*positive*	*-0.061*	*negative*
5	*142*	*+0.212*	*positive*	*-0.152*	*negative*
6	*62.61*	*-0.537*	*negative*	*+0.057*	*positive*

VI. CONCLUSION

Identification of the flicker source is the first step in improving the power quality of network. In this paper, a method is proposed which can be used to find several flicker sources in a non-radial network. In order to reduce number of measurement devices, buses voltages have been estimated from current values, where simulation results show the estimated values are accurate. Then by using envelope separation method and DFT algorithm flicker power calculated. By using the fundamental power flow direction at any line as reference, and flicker power sign, flicker sources have been detected correctly. Two different cases have been used to validate the algorithm.

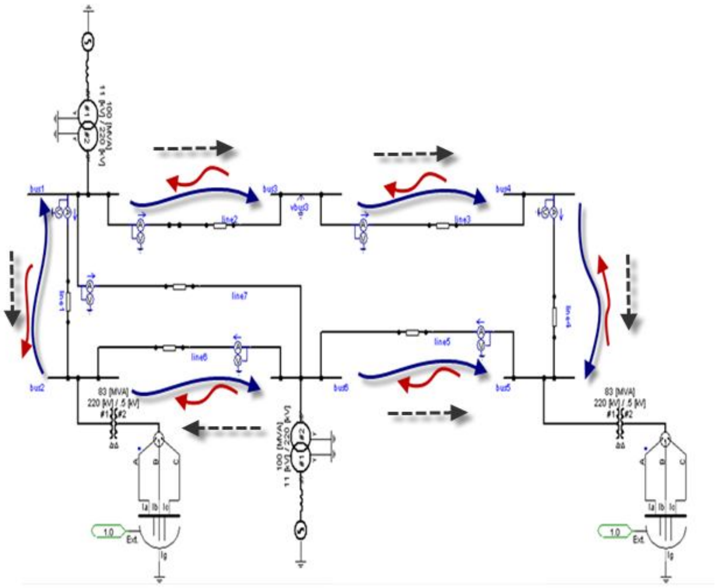

Fig. 14. Graphical simulation result of the second case

VII. APPENDIX

TABLE. V. LINES PARAMETERS

line	$R(\Omega)$	$X(\Omega)$
1	0.0018	0.0222
2	0.0018	0.0222
3	0.0018	0.02
4	0.0022	0.02
5	0.0022	0.02
6	0.0018	0.02
7	0.0022	0.0222

TABLE. VI. TRANSFORMERS PARAMETERS

$X(pu)$	$R(\Omega)$	Transformer number
0.026666	0.000001	1
0.026666	0.000001	2

TABLE. VII. GENERATORS PARAMETERS

Generator number	Connected bus	$X(pu)$
1	7	0.11999
2	8	0.11999

VIII. REFERENCE

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