

A Study of K-Factor Power Transformer Characteristics by Modeling Simulation

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Abstract— Harmonic currents generated by nonlinear loads can cause overheating and premature failure in power transformers. K-factor transformers are specially designed to accommodate harmonic currents and offer protection against overheating caused by harmonics. They minimize harmonic current loss and have an additional thermal capacity of known limits. According to IEEE C57-110, the winding eddy current losses are considered proportional to the harmonic current squared times its harmonic number. K-factor is only an indicative value and the authors' main objective in this paper is to study the effect of harmonics on oil filled transformer and to simulate harmonic behavior using Matlab Simulink. A case study is simulated in order to investigate K-factor values with pumping loads, with and without the use of harmonic filters. Results are compared with measured values.

Keywords—component; K-factor transformers; harmonics filter; total harmonic distortion

I. INTRODUCTION

In recent years, there has been an increased concern about the effects of nonlinear loads on electric power systems [1]. Harmonic currents adversely affect virtually every component in the power system, creating additional dielectric, thermal, and/or mechanical stresses [2]. The harmonic currents flowing through the power system impedances result in harmonic voltage drops which are observed as voltage distortions. Severe voltage distortions may occur when the power system's inductive and capacitive reactance's happen to be equal (parallel resonance) at one of the nonlinear load's significant harmonic current frequencies (typically the 5th, 7th, 11th or 13th harmonic) [2-5].

Even without resonance, harmonic currents cause losses in normal power system components. Wiring experiences additional heating beyond the normal I^2R , due to skin and proximity effects. Harmonics also cause over heating of the neutral conductor due to the additive nature of triple harmonics (3rd, 9th, 15th, etc.) on three phase four wire systems serving nonlinear loads with line-to-neutral connections [6, 7].

With transformers, harmonic load currents cause additional heating, primarily in the form of additional winding eddy current losses. IEEE C57.110, provides methods to de-rate a transformer for any given harmonic load profile [8].

K-factor transformers are specifically designed to accommodate harmonic currents and they have an additional

thermal capacity of known limits, allowing operation up to nameplate capacity without de-rating.

II. K-FACTOR TRANSFORMERS

K-factor rating is optionally applied to a transformer, indicating its suitability for use with loads that draw non sinusoidal currents. The K-factor is given by the following equation [6, 9].

$$K - Factor = \sum_{h=1}^{h=\max} I_h^2 h^2 \quad (pu) \quad (1)$$

where:

h = harmonic number, I_h = the fraction of total rms load current at harmonic number h

K-factor rated transformers have not been evaluated for use with harmonic loads where the rms current of any singular harmonic greater than the tenth harmonic is greater than 1/h of the fundamental rms current.

A. Relationship between K-factor and harmonic loss factor

The definition of the K-factor by the Underwriter's Laboratory (UL) [10] is based on using the transformer rated current in the calculation of per unit current in the previous equation. Substituting the rated current for the K-factor gives:

$$K - Factor = \sum_{h=1}^{h=\max} h^2 \left(\frac{I_h}{I_R} \right)^2 = \frac{1}{I_R^2} \sum_{h=1}^{h=\max} I_h^2 h^2 \quad (2)$$

where:

h is the harmonic order, I_h is the rms current at harmonic "h" (amperes), I_R is the rms fundamental current under rated frequency and rated load conditions (amperes).

The relationship of the harmonic loss factor and the UL K-factor [11-13] is given by:

$$K - Factor = \left(\frac{\sum_{h=1}^{h=\max} I_h^2}{I_R^2} \right) F_{HL} \quad (3)$$

The harmonic loss factor is a function of the harmonic current distribution and is independent of the relative magnitude. The UL K-factor is dependent on both the magnitude and the distribution of the harmonic current. For a

set of harmonic load current measurements, the calculation of the UL K-factor is dependent on the transformer rated secondary current. For a new transformer with harmonic currents specified as per unit of the rated transformer secondary current, the K-factor and harmonic loss factor have the same numerical values. The numerical value of the K-factor equals the numerical value of the harmonic loss factor only when the square root of the sum of the harmonic currents squared equals the rated secondary current of the transformer [14, 15].

B. Standard transformers K-factor ratings

The standard K-factor transformer ratings and typical loads are given in Table I [10].

TABLE I. K-FACTOR TRANSFORMER RATINGS

Load	K-factor
Incandescent lighting (with no solid state dimmers)	K-1
Electric resistance heating (with no solid state heat controls)	K-1
Motors (without solid state drives)	K-1
Control transformers/electromagnetic control devices	K-1
Motor-generators (without solid state drives)	K-1
Electric-discharge lighting	K-4
UPS w/optional input filtering	K-4
Induction heating equipment	K-4
Welders	K-4
PLC's and solid state controls (other than variable speed drives)	K-4
Telecommunications equipment	K-13
UPS without input filtering	K-13
Multi-wire receptacle circuits in general care areas of health care, facilities and classrooms of schools, etc.	K-13
Multi-wire receptacle circuits supplying inspection or testing equipment on an assembly or production line	K-13
Mainframe computer loads	K-20
Solid state motor drives (variable speed drives)	K-20
Multi-wire receptacle circuits in critical care areas and operating/recovery rooms of hospitals	K-20
Multi-wire receptacle circuits in industrial, medical, and educational laboratories.	K-30
Multi-wire receptacle circuits in commercial office spaces	K-30
Small mainframes (mini and micro)	K-30
Other loads identified as producing very high amounts of harmonics (especially in higher orders)	K-40

K-factor transformers are designed to be operated fully loaded with any harmonic load having a K-factor equal to or less than its K-rating. For example, a K-13 transformer can be fully loaded with any harmonic load having a K-factor up to K-13. If the load has a K-factor greater than 13, then the transformer cannot be safely operated at full load and would require de-rating [16].

For K-factor transformers, UL also requires that the neutral terminal and connections be sized to accommodate twice the rated phase conductor size (double the minimum neutral capacity) of standard transformers. Standard transformers, i.e. those not marked with a K-factor rating, may have some tolerance to nonlinear loading [16], but their capability is unknown to the user and is not certified by a third party such as

UL. Currently, marking a transformer with a K-factor rating is not required by UL.

III. CASE STUDY

The Toshka Pumping Station was constructed between 1998 and 2003. It is literally the largest state project in Egypt. Located along the shores of the Nasser Lake, which was created by the construction of the famous, Aswan Dam, this pumping station is a project in which Hitachi, Ltd. installed 21 large vertical centrifugal volute pumps with the capacity to draw 29 million cubic meters of water per day and supply it to the desert area. About 2,250 square kilometers of land are to be greened through this project [17, 18]. A view of the Toshka pumping station is illustrated in Figure 1.



Fig. 1. Toshka Pumping Station

A. Description of Toshka pumping station

The pumping station, which is located at the intake basin, will accommodate (in the final stage) 24 variable speed pumps with a total capacity of 288MW (24 x 12MW) and a total discharge of 400 m³/s (24 x 16.7m³/s). The static suction head is 56m. The pumping station dimensions are 145 x 60 x 45m (l x h x w). The electrical supply to the plant is secured via a 220/11KV substation in Toshka and an 11 kV bus duct, which were also supplied by ABB in a separate contract under the Toshka Project. Figure 2 represents the single line diagram of 220kV substation to 11kV Toshka pump station.

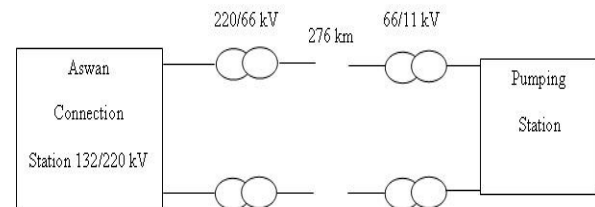


Fig. 2. Connection between Aswan connection substation and Toshka pumping station

B. Measurement Technique

The harmonics measurement location is shown in Figure 3, the point of common coupling is the most important point of

harmonics measurement, and it is located on the output of the 66/11 kV, 25MVA transformers. Measurements of the harmonic currents and K-factor calculations for Toshka pumping station without harmonic filter are shown in Table II and with harmonic filter are shown in Table III. The measurements are carried out on phase B. From the measurement values it is shown that the K-factor for the system without harmonic filter is equal to 5.436679, whereas the K-factor for the system with harmonic filter is equal to 1.200575, which means that the use of the harmonic filter decreases the selected K-factor transformer ratings almost five times.

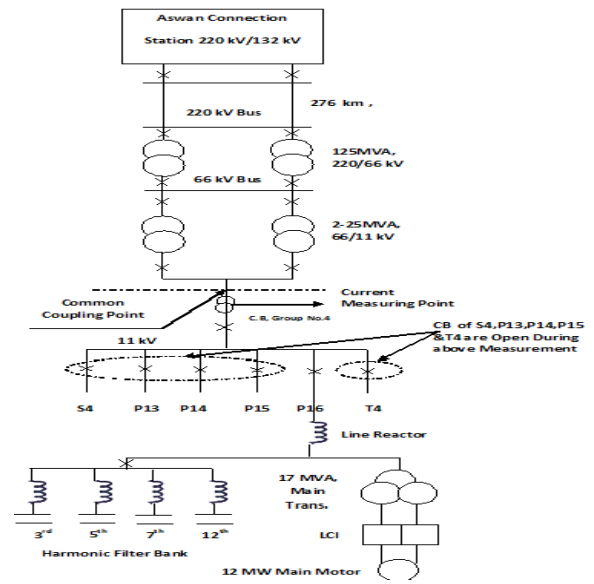


Fig. 3. Single line diagram of Toshka pipping station

TABLE II. HARMONICS MEASUREMENT WITHOUT FILTER

H	I _H % fund	I _H	I _h = I _H / I _{rms}	H ² *(I _h) ²
1	100	1	0.996924891	0.993859237
3	2.5591	0.025591	0.025512305	0.005857899
5	6.8061	0.068061	0.067851705	0.115096347
7	2.263	0.02263	0.02256041	0.024939633
9	0.12456	0.0012456	0.00124177	0.000124901
11	1.4063	0.014063	0.014019755	0.023782976
13	1.3018	0.013018	0.012977968	0.028464274
15	0.05778	0.0005778	0.000576113	7.46789E-05
17	0.09951	0.0009951	0.00099208	0.00028444
19	0.08968	0.0008968	0.000894102	0.00028859
21	0.05123	0.0005123	0.000510755	0.000115044
23	0.20088	0.0020088	0.002002623	0.002121553
25	0.07366	0.0007366	0.000734425	0.000337112
27	0.05600	0.0005600	0.000558298	0.000227227
29	0.04900	0.0004900	0.000488563	0.000200741
31	0.09088	0.0009088	0.000906025	0.000788867
33	0.04416	0.0004416	0.000440302	0.00021112
35	0.05046	0.0005046	0.000503138	0.000310106
37	0.05041	0.0005041	0.00050256	0.000345763
39	0.04367	0.0004367	0.000435377	0.00028831
41	0.03704	0.0003704	0.000369321	0.000229285
43	0.04254	0.0004254	0.000424142	0.000332628
45	0.04760	0.0004760	0.000474586	0.000456095
47	0.07259	0.0007259	0.000723728	0.001157034
49	0.05342	0.0005342	0.000532647	0.000681194
Σ			K=	1.200575

TABLE III. HARMONICS MEASUREMENT WITH FILTER

H	I _H % fund	I _H	I _h = I _H / I _{rms}	H ² *(I _h) ²
1	100	1	0.996197	0.992408
3	0.36702	0.0036702	0.003656	0.00012
5	0.45481	0.0045481	0.004531	0.000513
7	0.68039	0.0068039	0.006778	0.002251
9	0.30952	0.0030952	0.003083	0.00077
11	0.011008	0.00011008	0.00011	1.46E-06
13	5.501	0.05501	0.054801	0.507528
15	0.12257	0.0012257	0.001221	0.000335
17	0.19933	0.0019933	0.001986	0.00114
19	0.26443	0.0026443	0.002634	0.002505
21	0.19914	0.0019914	0.001984	0.001736
23	4.4975	0.044975	0.044804	1.061911
25	3.1756	0.031756	0.031635	0.625492
27	0.14193	0.0014193	0.001414	0.001457
29	0.21729	0.0021729	0.002165	0.003941
31	0.21076	0.0021076	0.0021	0.004236
33	0.15327	0.0015327	0.001527	0.002539
35	2.6503	0.026503	0.026402	0.853918
37	2.0062	0.020062	0.019986	0.546817
39	0.13907	0.0013907	0.001385	0.002919
41	0.21042	0.0021042	0.002096	0.007386
43	0.17302	0.0017302	0.001724	0.005493
45	0.12539	0.0012539	0.001249	0.00316
47	1.4933	0.014933	0.014876	0.488855
49	1.1575	0.011575	0.011531	0.319245
Σ			K=	5.436679

C. Modeling of Toshka pumping station

Toshka pumping station consists of four groups and each group contains six synchronous motors. The simulation model is consisted of the Aswan connection station 132/220 kV, two transmission lines 220 kV (distance 276km), two transformers 125MVA, 220/66 kV and two transformers 25MVA, 66/11kV. Figure 4 shows the model of the pumping station, transmission lines and the power transformers. Figure 5 shows the control and drive circuits for the synchronous motor.

D. Results

The modeling results are obtained on the output of the 66/11kV, 25 MVA transformer for the following two cases

Case (1) without using harmonics filter:

Figures 6-9 show voltage and current (phase and 3-phase) at low tension of 25MVA 66/11kV transformer.

Figures 10-11 show the frequency response characteristics without harmonic filter for voltage and current respectively. The harmonics of currents and voltages are listed in Table IV. The 5th, 7th and 11th harmonics exceeded the limits recommended by IEEE-519 [9]

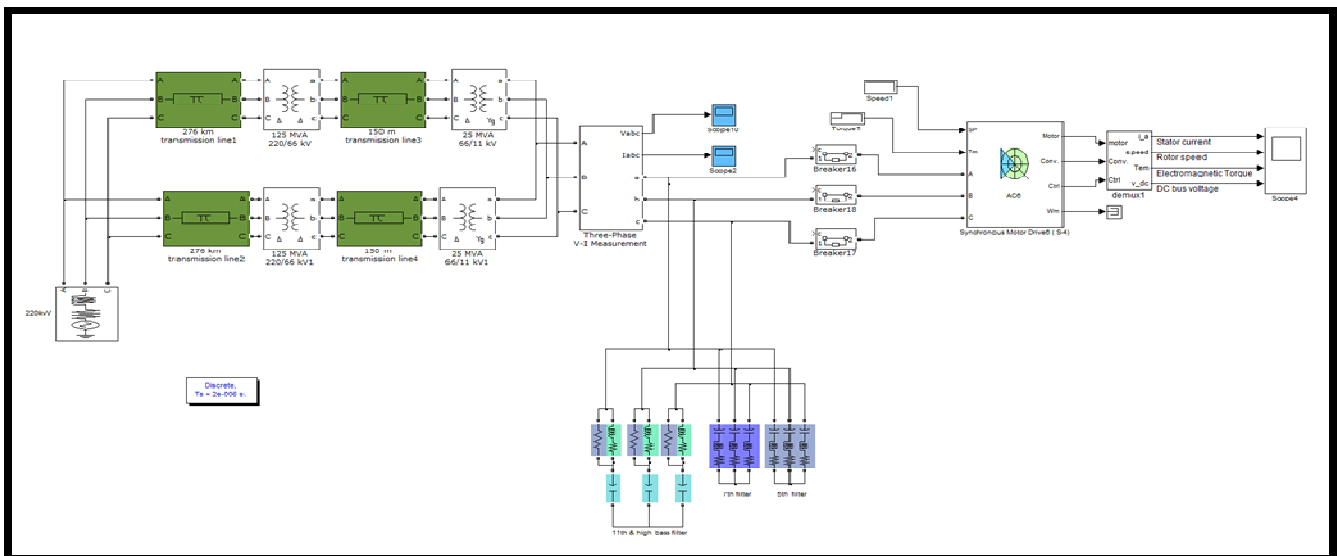


Fig. 4. Modeling of Toshka Pumping Station, transmission lines and the power transformers

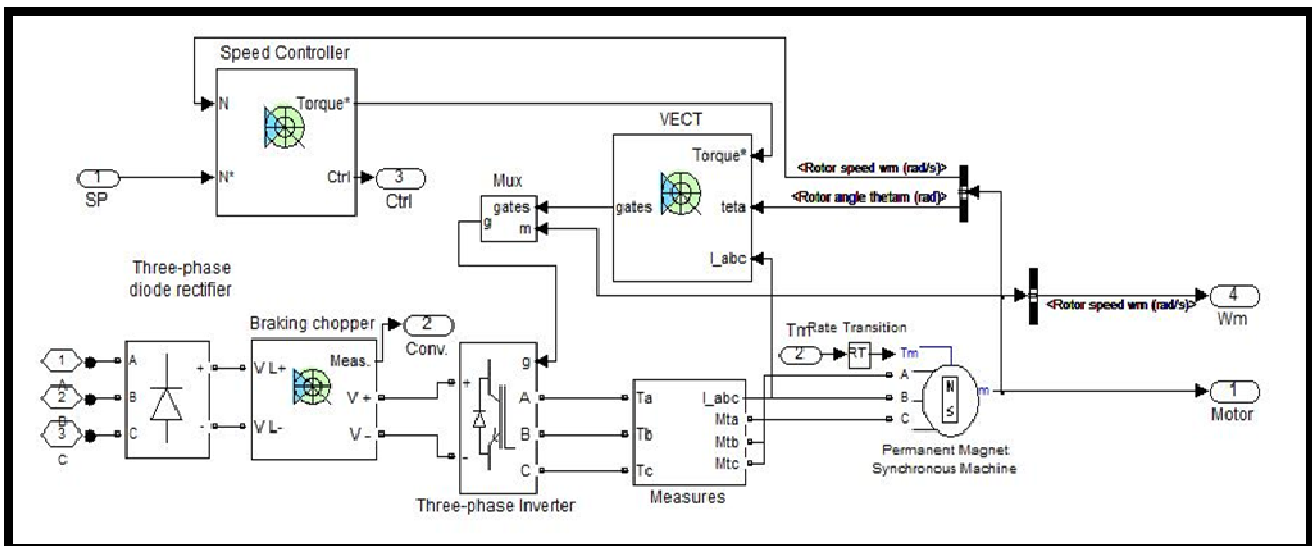


Fig. 5. Control and drive circuit for the synchronous motor

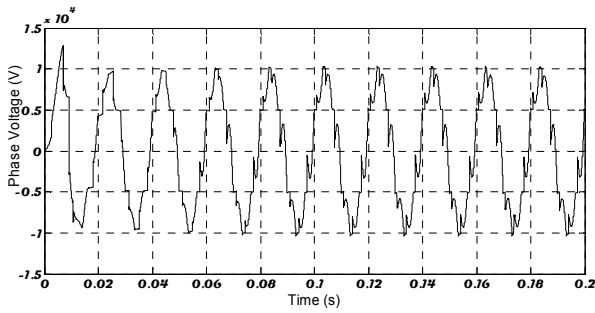


Fig. 6. Phase voltage at low tension side of 25MVA 66/11kV transformer without harmonic filter

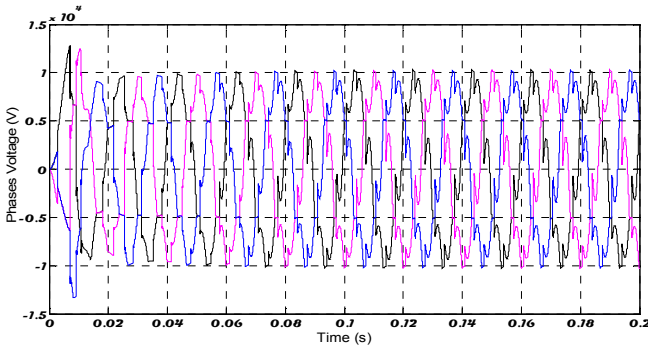


Fig. 7. 3-Phase voltage at low tension side of 25MVA 66/11KV transformer without harmonic filter

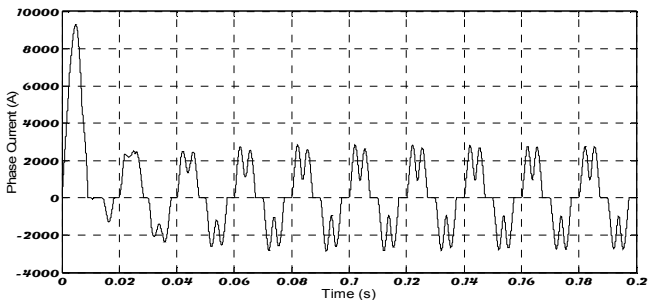


Fig. 8. Phase current at low tension side of 25MVA 66/11KV transformer (without harmonic filter)

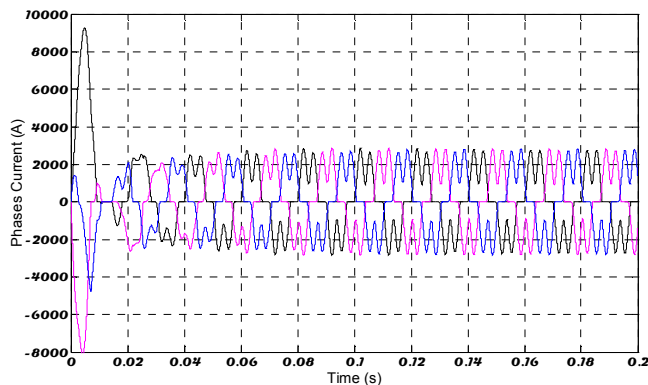


Fig. 9. 3-Phase current at low tension side of 25MVA 66/11KV transformer without harmonic filter

TABLE IV. THD FOR VOLTAGE AND CURRENT WITHOUT USING FILTER

Harmonic order	Harmonic voltage % If	Harmonic current % If
3	1.72	2.92
5	9.29	41.11
7	11.49	11.29
11	6.17	3.53
THD	17.64 %	42.93 %

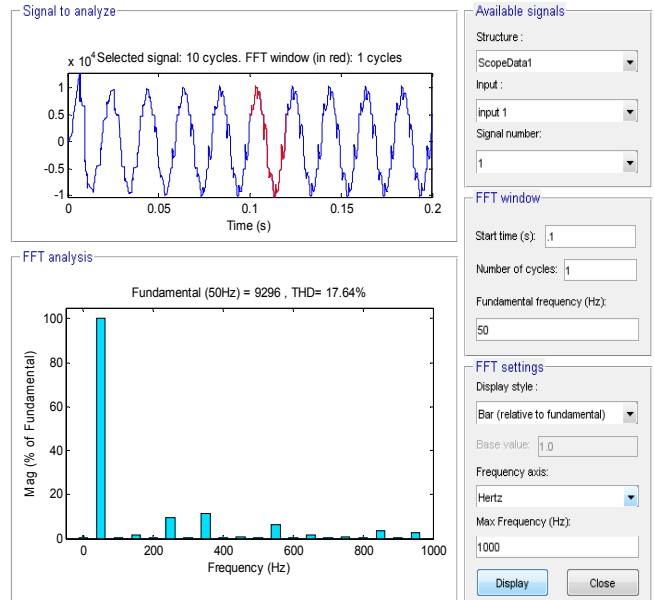


Fig. 10. Voltage and frequency response characteristics without harmonic filter

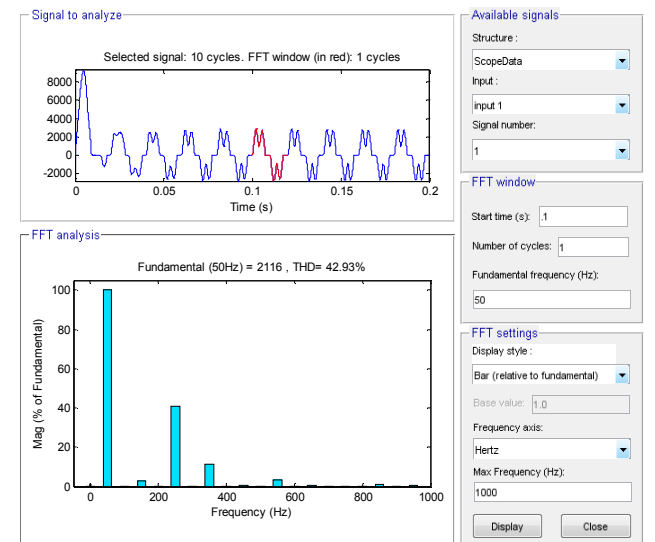


Fig. 11. Current and frequency response characteristics without harmonic filter

Case (2) by using harmonics filter

Figures 12-13 show 3-phase voltage and current at low tension of 25MVA 66/11kV transformer respectively with harmonic filter. Figures 14-15 show the frequency response characteristics when using harmonic filter for voltage and

current respectively. The total harmonic distortion for current and voltage with and without the use of the harmonic filter is listed in Table V. The calculated K-factor for the simulated model with and without harmonic filter is shown in Table V. The K-factor without the use of the harmonic filter is 5.1497 which is five times greater than the K-factor calculated when using the harmonic filter. Therefore, when a harmonic filter is employed, the K-factor rating used is K1 or K4 whereas a K-factor rating of K7 is used when a harmonic filter is not employed. The K-factor calculated from the measured values taken from the station is approximately equal to the calculated values of the simulated model.

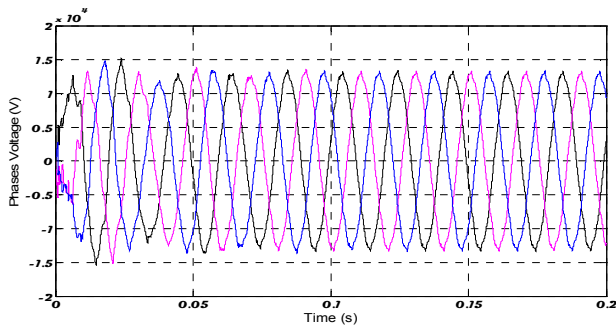


Fig. 12. 3-Phase voltage at low tension side of 25MVA 66/11KV transformer with harmonic filter

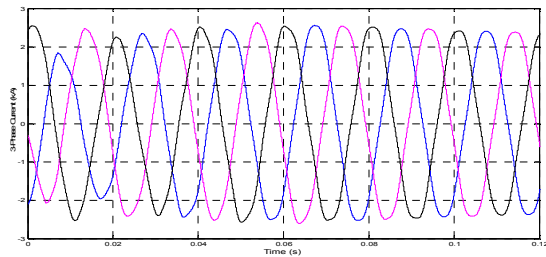


Fig. 13. 3-Phase Current at low tension side of 25MVA 66/11KV transformer with harmonic filter

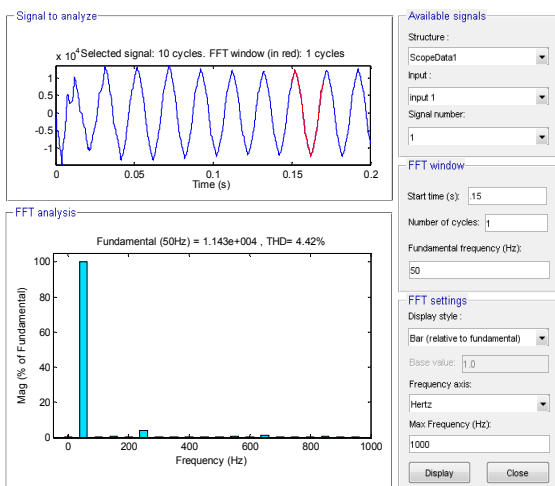


Fig. 14. Voltage and frequency response characteristics with harmonic filter

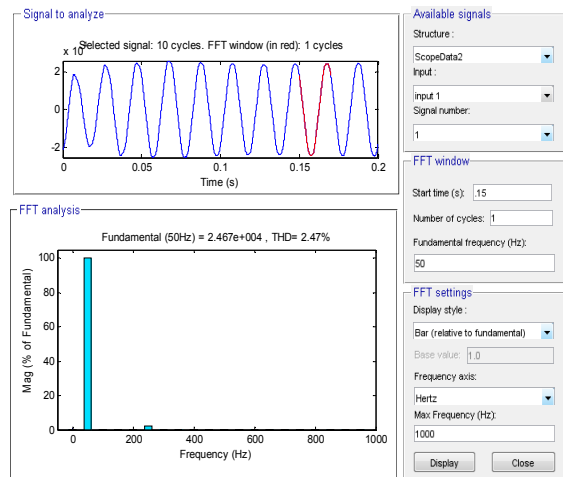


Fig. 15. Current and frequency response characteristics with harmonic filter

TABLE V. K-FACTOR AND THD FOR VOLTAGE AND CURRENT

	Without Harmonic Filter		With Harmonic Filter	
	THDu%	THDI%	THDu%	THDI%
	17.64	42.93	4.42	2.47
IEEE-519 recommended Limit			5%	5%
K-factor From measured values	5.436679		1.200575	
K-factor From modeling	5.1497		1.0147	

IV. CONCLUSION

In this paper a study of K-factor power transformer characteristics is presented. A case study (Toshka pumping station) is simulated with the use of Matlab Simulink. The total harmonics distortion at the output of 25MVA, 66/11KV transformer with and without harmonic filter is calculated. Measured harmonics current and calculated K-factors with and without filters are in agreement with the results obtained by the suggested model.

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