Power Quality Assessment for a Fluctuating Load Based on the Electrical Transient Analysis Program

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Abstract. Before a new power customer is connected into the power grid, it is an important task to assess the possible impact of this new load on the power quality. This paper proposes a method to analyze the voltage fluctuations and harmonics for the characteristics of many types and quantities of internal frequency conversion equipment and motors in the power consumer. First, the principles and methods for model establishment of voltage fluctuation analysis and harmonic analysis are introduced. Then, according to the actual operation of the loads, the simulation model is established in ETAP (Electrical Transient Analysis Program). The voltage fluctuation and the harmonics injected into the power grid caused by the operation of loads are obtained through simulation. Since the phenomenon that the harmonics exceed the standard in the extreme operating condition, this paper gives reasonable control measures based on the actual condition of the load, the simulation results and the allowable values prescribed by national standards.

1. Introduction
With the development of social economy, the type of electrical equipment in the power system tends to be complex, especially the use of non-linear, large-capacity, percussive loads and various motors, which seriously affect the power quality. Therefore, motor start analysis and harmonic analysis are indispensable when a new industry power consumer wants to access to power grid.

The ETAP can achieve power flow analysis, short circuit analysis, generator/motor start analysis, harmonic analysis, and optimization of power flow. The reference [1] introduces the principle and method of the synchronous motor starting, and it also analyzes the advantages and disadvantages of different motor starting methods. The reference [2] introduces the motor starting calculation program and motor model parameter setting in ETAP software. The function of ETAP software and specific harmonic analysis case are introduced in [3]. In the above references, the power quality analysis is just for the individual load, however power quality analysis for various kinds of aggregated loads has not been performed.

This paper proposes a method to analyze power quality of the aggregated loads for the new power consumer. Firstly, the same kind of loads are equivalent to a large load, and then a simulation model is established for calculation and analysis. This method can comprehensively analyze the power quality problems existing in the power system and provide reference for decision-making of related departments.

The paper is organized as following: the models of voltage fluctuation analysis and harmonic analysis are presented in the Section 2, then the simulation cases for the voltage fluctuation and harmonic are
shown in the Section 3, and the governance measures against excessive harmonic are given in Section 4, finally the main conclusions are drawn in Section 5.

2. The establishment of simulation analysis model

For the new power consumer with a large number of motors and frequency conversion equipment, voltage fluctuations and harmonic problems may occur when they are operated. Therefore, this section mainly establishes the simulation models about these two power quality problems in the ETAP software.

2.1. The model of voltage fluctuation analysis

Since there are kinds of motors in the power consumer, the starting mode is different, and the number of each type of motors is huge. Therefore, in the analysis process, firstly, the characteristics of various starting modes of the motors are analyzed, and the following conclusions are drawn: Direct starting has the characteristics of large torque and short starting time, but also has great impact on the power grid. The step-down starting is to connect the motor using delta connection method to Y type at the starting time, and the starting current is 1/3 of the original, but it will still cause the large voltage fluctuation when the original starting current of the motor is large. Variable frequency starting allows the motor to start smoothly with constant frequency adjustment by the inverter. The starting current is limited to near rated current and there is almost no impact on the power grid.

In view of the above-mentioned characteristics of the starting mode, in combination with the actual starting mode of the motor in the power consumer, the effects of the direct starting and the step-down starting are mainly considered in the analysis process of the voltage fluctuation. During the process of building the model, the actual starting conditions of the motors are analyzed. The motors which are started at the same time are identified and classified according to the starting mode, and then multiple motors of the same type and simultaneously started are equivalently superimposed as one big motor. The models of different equipment are established separately, and a simulation system is established according to the operating conditions of the equipment for simulation calculation.

There are two kinds of motor starting calculation methods in ETAP: static motor starting and dynamic motor starting. This paper mainly studies the fluctuation of the grid voltage when the motor starts, so the static motor start analysis will be performed.

2.2. The model of harmonic analysis

The existence of a large number of internal frequency conversion equipment in the power consumer causes the system to generate lots of harmonics. When the simulation model is built to analyze the harmonics injected into the grid by the internal loads operation, the inverter that generates harmonics during operation is equivalent to a static load with a harmonic current source. However, due to the great differences in the harmonic characteristics of different frequency conversion devices, it is necessary to perform equivalent processing on harmonic source devices that are operating at the same time.

When there are multiple harmonic sources in the system, if the harmonic currents of the two harmonic sources are added and calculated on the same phase of one line, the equation (1) is used when the phase angle is known:

\[ I_h = \sqrt{I_{h1}^2 + I_{h2}^2 + 2I_{h1}I_{h2} \cos \theta_h} \] (1)

In the formula, \( I_{h1} \) and \( I_{h2} \) are the hth harmonic current of harmonic source 1 and harmonic source 2 respectively, and \( \theta_h \) is the phase angle between harmonic source 1 and harmonic source 2.

In the actual power system, the phase angle is usually uncertain. Then, it can be calculated according to equation (2):

\[ I_h = \sqrt{I_{h1}^2 + I_{h2}^2 + K_h I_{h1}I_{h2}} \] (2)

The \( K_h \) is the calculation coefficient, and its value is selected according to Table 1.
Table 1. The value of $K_h$.

| The number of harmonics | 3   | 5   | 7   | 11  | 13  | other |
|-------------------------|-----|-----|-----|-----|-----|-------|
| $K_h$                   | 1.62| 1.28| 0.72| 0.18| 0.08| 0     |

When two or more harmonic currents are superimposed, the two harmonic currents are superimposed first, then superimposed with the third harmonic current, and so on.

In accordance with the above method, different harmonic equivalent model is established according to the actual distortion rate of the device. Then, according to the actual operating conditions, the simulation system under extreme operating conditions is established, and the harmonic current generated during the operation of the equipment is simulated and analyzed.

3. Case study

3.1. The simulation model of a power consumer

The power consumer consists of frequency conversion starting motors, direct starting motors, frequency conversion conditioners, elevators, lighting and other loads. The wiring diagram to analyze the voltage fluctuation caused by the operation of the equipment is shown in Figure 1. Since the frequency conversion starting has almost no impact on the power grid, this analysis model mainly considers the direct starting motor in Figure 1. The loads started via direct starting, including 30kW drainage pump, 26kW dehumidifier, 45kW ventilator and 40kW crane. In order to simulate the most serious motor starting situation, the above motor is equivalent to a large motor with a power of 141 kW. The wiring diagram to analyze the harmonics caused by the operation of the equipment is shown Figure 2. To analyze the extreme operating conditions, 458 small converter with the power of 6.13 kW supplied by No.1 transformer and No.1 transformer, 24 small converter with the power of 5 kW supplied by No.2 transformer and the large frequency conversion equipment with the power of 1 MW supplied by 10 kV are equivalent to the static harmonic source loads. The actual harmonic content of static loads is shown in Table 2. In Table 2, the less than 25th harmonic of No.5 load is 0 because it is PWM type inverter and only generates harmonics at the switching frequency.

![Figure 1. The model of motor starting](image1)

![Figure 2. The model of harmonic analysis](image2)

Table 2. The harmonic content of static loads

| Harmonic order | 5   | 7   | 11  | 13  | 17  | 19  | 23  | 25 |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|
| No.1 and No.3 load | 13.57 | 0.74 | 0.29 | 0.13 | 0.06 | 0.04 | 0.02 | 0.02 |
| No.2 load | 3.7 | 1.2 | 6.9 | 3.2 | 0.3 | 0.2 | 1.4 | 1.3 |
| No.5 load | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
3.2. Voltage fluctuation analysis

Figure 3. The simulation results of voltage fluctuation

In order to obtain the magnitude of the voltage fluctuation in the extreme condition, the motor starts at 1 second, and the starting time is 4 seconds. After that, the motor runs in a stable state. The results are shown in Figure 3. From Figure 3, it can be seen that the voltage of the power grid decreases from 1.00p.u. To 0.991p.u. At 1 second. The voltage is restored to the rated value at the end of motor starting, i.e. at 5 seconds. From Figure 3, it can be seen that the voltage fluctuation of the power grid caused by motor starting is less than 1% under the extreme condition. Comparing GB/T 12326-2008 “Voltage fluctuations and flicker of power quality” [4], the results show that the voltage fluctuations caused by the motor starting within this power consumer meet the requirements of national standards.

3.3. Harmonic Analysis

According to Figure 2, the above harmonic simulation model is analyzed and calculated, and the results of harmonic current are shown in Table 3. Referring to GB/T 14549-1993 “Power Quality Harmonics in Public Power Networks” [5], it can be concluded that when the internal loads of the power consumer operates under the extreme condition, the 5th harmonic current exceeds the national standard and other order harmonics are within the requirements of the national standard [6].

Table 3. The results of harmonic current.

| Harmonic order | Current allowable value (A) | Current (A) |
|----------------|----------------------------|-------------|
| 5              | 6.957                      | 16.602      |
| 7              | 6.319                      | 0.800       |
| 11             | 5.058                      | 0.329       |
| 13             | 4.504                      | 0.135       |
| 17             | 3.569                      | 0.037       |
| 19             | 3.212                      | 0.023       |
| 23             | 2.677                      | 0.010       |
| 25             | 2.439                      | 0.010       |

4. Governance measures and recommendations

From the above simulation results, it can be seen that the harmonics generated by the operation of the loads may exceed the allowable values in the national standards. Therefore, it is necessary to formulate appropriate harmonic control measures to suppress harmonics [7]. The specific governance measures are as follows:

(1) The active power filter (APF) installed on the low-voltage side
The APF can monitor the current in real time and generate a compensation current to compensate or cancel the harmonic current. By analyzing the harmonic characteristics of each operating load, it was found that more harmonic currents caused by No.1, No.2, and No.3 loads during operation are injected into the 10kV power bus via No.1 Bus and No.2 Bus. Therefore, a reasonable-capacity APF is installed on the two low-voltage bus-sides to achieve dynamic compensation of harmonics.

| #      | 5th harmonic current of No.1 bus (A) | 5th harmonic current of No.2 bus (A) |
|-------|-------------------------------------|-------------------------------------|
| Before the governance | 204.88                             | 218.24                             |
| The compensation current of APF | 190 | 190 |
| After the governance | 14.88 | 28.24 |

After being treated by two APFs with the capacity of 200A, the fifth harmonic current at the low voltage side of the transformer is shown in Table 4.

After installing APFs on the low-voltage side of transformers, the calculation results of 5th harmonic current on the 10kV side is 1.578A according to equation (2), less than the allowable value of national standard.

(2) Reserving passive filter devices on the high voltage side

In order to improve the filtering effect and take the uncertainties of the filtering for the high-voltage load (No.5 inverter load) into account, a passive filter device is installed on the high-voltage side as a backup. Ensure that the harmonic current on the 10kV bus meets the requirements of national standard when the load is operating.

From the calculation result of measure (1), it can be seen that the above-mentioned harmonic control measure can solve the existing harmonic problems for a new power consumer that contains vast frequency conversion equipment.

5. Conclusion

In this paper, a 10kV power supply system for a power consumer is set up in the ETAP software, then the voltage fluctuation analysis and harmonic analysis are performed. From the simulation results, it can be seen that the voltage fluctuation caused by starting the motor is lower than the national allowable value. When the power consumer is operating in the extreme condition, the 5th harmonic current exceeds the national allowable value. In order to maintain the 5th harmonic current to be lower than the national allowable value, the APFs are installed on the low-voltage side of transformers. The harmonic emitting levels are restricted to be a permitted level after the mitigation measures are installed. Therefore, power quality analysis based on ETAP software is useful to find problems in advance and take appropriate measures beforehand.

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References

[1] Z.Q. Chang, Simulation research on variable frequency starting of synchronous motor based on ETAP, Electrical Engineering Technology, 12 (2016) 22-24 (in Chinese).
[2] J.J. Dai, Y.L. Jia, Soft start simulation and calculation of motor based on power system analysis software ETAP. The proceedings of the fifth national petroleum and chemical industry electric management (technology) symposium. Yanji, Jilin, China, 2006: 196-203 (in Chinese).
[3] J. Zheng, T. Lin, et al, Harmonic analysis of power grid based on power system analysis software ETAP, Power System and Clean Energy, 27 (2011) 7-12 (in Chinese).
[4] GB/T 12326-2008 Power quality voltage fluctuation and flicker (in Chinese).
[5] GB/T 14549-1993 Harmonics of power quality public grid (in Chinese).
[6] L.Y. Li, S.L. Hou, X.H. Gu, Analysis and suppression of power harmonics in direct air cooling unit factory based on ETAP simulation, Electric Power Science and Engineering, 28 (2012) 18-24 (in Chinese).

[7] E.J. Davis, A.E. Emanuel, D.J. Pileggi, Harmonic pollution metering: theoretical considerations, IEEE Transactions on Power Delivery, 15 (2000) 19-23.