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Impact on power supply systems by electric arc furnaces simultaneously operating

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Abstract: Electric arc furnaces (EAFs), typical impact loads, are studied by ATP/EMTP on neighboring generators including electromagnetic torque fluctuation and excitation system response. EAFs models are built and inserted into EMTP/ATP from field tests or measurements. The results would give some positive advices to utility operators. At the same time, the simultaneity of EAFs operating is also studied. The worst effect of EAFs is concerned, especially when all EAFs start to work or stop almost simultaneously. Finally, it may be noted that, lots of EAFs may cause some damage to generators and should be paid much attention to. This modeling method can be used to evaluate the impacts of existing or planned nonlinear loads, and select the connection points of new EAF.

Keywords: Electric Arc Furnace, Modeling, Excitation System, Simultaneity, EMTP

1 Introduction

An electric arc furnace (EAF) is an unbalanced, nonlinear and time varying load, which can cause many problems to a power system and other users. Most consideration has already been paid into power quality problems, such as, flicker, harmonics and the like. A lot of research work has been done to build the arc furnace models to investigate these problems. Historically, these models are based on either the simplified V-I characteristic method, or the empirical formulas related to the arcing process. In [1], the arc furnace load is modeled by EMTP as a voltage source and the model is based on the V-I characteristics, using the sinusoidal variation of the arc resistance and bandlimited white noise variation as well. Another model is proposed in [2], which consists of the nonlinear, time varying resistance where both sinusoidal and stochastic time variation rules of arc length are considered. In order to consider the uncertainty of the process, the chaos theory is also used in arc furnace modeling [3,4]. In reference [5] the electrical model of an electric arc furnace integrates with thermal model for its performance evaluation. The effect of different arc furnace models on voltage disturbance is reviewed in [6,11].

However, the previous models are not suited to discuss the influence of impact on power supply system for the following reasons:

1) EAFs mentioned above are modeled either a voltage source or a current source, the relation between v and i is described either through V-I characteristic or relevant mathematical equations. It is difficult for them to reflect the real characteristic of EAFs because of their respective stochastic and time varying characteristic, which is often not according to the V-I characteristic. Furthermore, it is trouble to build tens of models of EAFs one by one.
2) Nowadays, with some compensation apparatus switching on, such as, SVC, STATCOM, a set of passive or active filters [7], UPFC and SMES [8], these quality disturbances might have less impact on HV supply systems. So, the field measurements acquired at PCC include not only the action of EAF but also these compensators. Models proposed above are not accurate if they use these field data.
3) From the point of view of power system operators, the influence on the PCC and its neighboring generators are received more attention. As a result, it is not necessary to build detail mechanism models for impact loads. It is already enough only to simulate their impact on power systems.

As the popularity and use of the arc furnace loads increase, some negative influence will be given on nearby generators due to their randomly electric behavior and the intermittent operating cycle. Especially, the sudden change of power might be detrimental to nearby generator and its accessories and affect the generator's Fatigue Life Expenditure (FLE).

Along with several impact loads congregating at certain subnet, the affected level of simultaneity of EAFs is concerned. When the network structure changes, the influence of EAFs on the power supply system will change too. Both system operators and network development planners will care about the change degree.

This paper presents some field measurements in Jiangsu Province of China to show the impact to the power supply systems from EAFs or other impact loads. Some researches are introduced on arc furnace modeling of such nonlinear time-varying characteristics by using EMTP. The further discussion is proposed after EAFs modeling, including the discussion of their influence on close-by generators, the reflection to the power systems caused by the simultaneity of EAFs, the change of network structure, and different connect points.

2 Arc furnace modeling based on field measurements

The measurements were carried out on the point of common coupling (PCC). The three-phase voltages at PCC, three-phase active power and reactive power were acquired during the whole process of an arc furnace operating. Apparently, the data included the effects of compensation equipments and arc furnace transformer tap changer. To simulate the voltage fluctuations and flicker, a controlled voltage source (CVS) should be used and connected with PCC, and enough accuracy is also obtained. The power consumption from the power system is represented as a controlled current source (CCS) since voltage at PCC is controlled by a CVS. Therefore, an arc furnace model is to put a CVS and a CCS together: CVS simulates the PCC voltage disturbances and CCS the power changes. CVS and CCS can be easily inserted in EMTP by transient analysis of control system (TACS) module.

Taking into account impacts on neighboring generators, it is unnecessary to simulate a long time. The simulation of sudden ascending or descending changes of power will be preferred. The typical simulating duration is about 10 seconds or shorter.

2.1 The EAF CCS and CVS formula

The field measurements, $I_{k,RMS}$, P_k , Q_k , and $U_{k,RMS}$ $(k=a,b,c)$, are acquired as shown in Fig.1. $I_{k,RMS}$, P_k , Q_k are phase current RMS(Root Mean Square) value, phase active power and phase reactive power flowing through PCC to EAFs respectively. $U_{k,RMS}$ is the phase voltage RMS value at PCC.

In order to simulate the imbalance among three phases, single-phase model is used here.

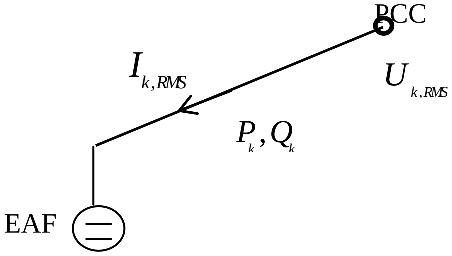

Fig.1 Measurements acquired from field tests

So, the instantaneous phase current from PCC to EAF, i_k, is calculated as equation (1). Similarly, the instantaneous voltage at PCC is obtained by equation (2).

$$i_k = \sqrt{2} I_{k,RMS} \cos(\omega t + \phi_{kv} - \varphi_k) \qquad (1)$$

$$u_k = \sqrt{2} U_{k,RMS} \cos(\omega t + \phi_{kv}) \qquad (2)$$

Where, $\varphi_k = a\tan(Q_k / P_k)$, is the angle between the current and the voltage at PCC. ϕ_{kv} is the angle of voltage at PCC. Here, $\phi_{kv} = \phi_{kv0}$ is used and ϕ_{kv0} is got from stead-state power flow calculation.

2.2 Modeling Procedure

The process of modeling EAF CCS in EMTP is illustrated as follows and the process of modeling CVS is similar:

1. Select the appropriate segment from field data, including $I_{k,RMS}$, P_k, Q_k, and $V_{k,RMS}$ $(k=a,b,c)$.
2. Calculate $\varphi_k = a\tan(Q_k / P_k)$.
3. Write $I_{k,RMS}$ and φ_k in EMTP by using TACS card 56 respectively, calculate i_k according to equation (1).
4. Use controlled source 60 in EMTP to transmit i_k from a TACS variable to a current source.

2.3 Model Initialization

Take CCS as an example and the CVS is in similarity. In EMTP, the value of controlled source 60 equal to zero at steady-state situation. So, steady-state initialization of the EAF current source should be completed before time-step solution. In this paper, a simple but effective initialization method is used. As shown in Fig.2, a controlled current source (card 60 in EMTP) and a common current source (card 14 in EMTP) are connected to the PCC through switch 1 and switch 2 respectively. The switch 2 is closed while switch 1 is opened at steady-state situation. At a certain switch time, the switch 2 is opened and switch 1 closed.

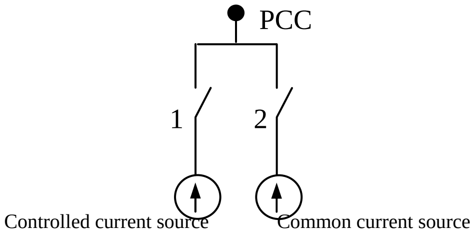

Fig.2 Model Initialization

Two aspects should be paid into consideration. One is the value of the controlled current source must equal to that of the common source at the switch time, the other is the switch time. In EMTP, the real opening time lags more or less. Therefore, a certain closed time should be decided according to the actual opening time of the corresponding switch 2.

2.4 Model Testing

The relative part of the test system is shown as figure I in appendix. Generators and their excitation systems are shown in section 3. Fig.3~Fig.5 illustrate the relative results of ATP/EMTP simulation and field data. Fig.3 shows the voltage at bus PC. In Fig.3 (a), the voltage sag occurs in ATP/EMTP simulation lags field data. Whereas they are the same at Fig.3 (b). The reason is the test equipments not in-phase. Due to the discrepancy shown at Fig.3(a), an impact occurs at 1.5 second at PC-SZJ #1line and another impact occurs at 2.4 second at PC-SZJ #2 line. Fig.4 (a) and Fig.5 (a) show the active power of EMTP simulation and the field data. Their discrepancies are not obvious. Fig.4 (b) and Fig.5 (b) give the reactive power of EMTP simulation and the field data. They response perfectly. So modeling by CCS + CVS module can be used to simulate such impacts.

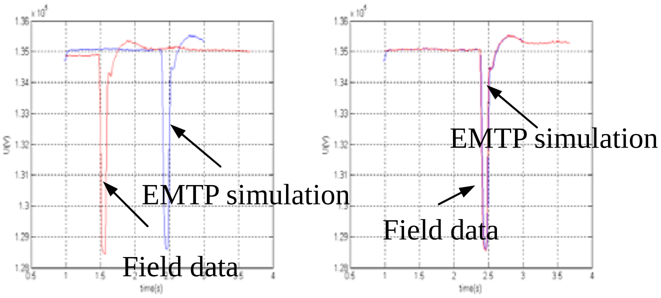

Fig.3(a) Voltage at PC measured at PC-SZJ #1 line (Phase A) Fig.3(b) Voltage at PC measured at PC-SZJ #2 line (Phase A)

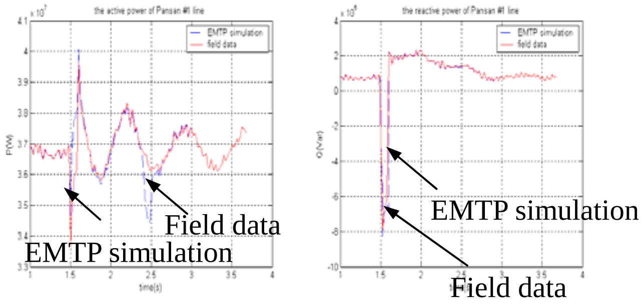

Fig.4(a) Active power through PC-SZJ #1 line (Phase A) Fig.4(b) Reactive power through PC-SZJ #1 line (Phase A)

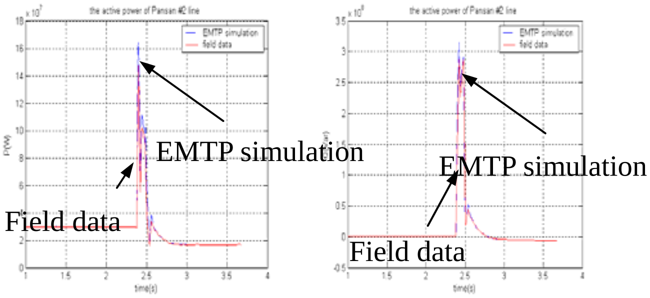

Fig.5(a) Active power through PC-SZJ #2 line (Phase A) Fig.5(b) Reactive power through PC-SZJ #2 line (Phase A)

3 Impact On Generators By CVS + CCS Module

3.1 Introduction of Test System

The test system is Jiangsu Province transmission networks, that is, the network of 220kV and above, shown at Fig.I in appendix. All detailed models are written in ATP/EMTP. The parameters of the power supply system were acquired by professional filed tests, including 735 transmission lines, 111 transformers and 85 generators and their excitation systems.

The other loads are set as invariable reactance. In this section, only the impact load at bus SZJ is taken into considered. The voltage at bus PC is set as a CVS and the current from PC to SZJ are set as a CCS.

3.2 Modeling Generator and its Excitation System in EMTP

Just as an example, this paper only presents a generator and its excitation model here. There are two same generators at plant 1. The prototype of excitation system of #2 generator is given at Fig.8a and the model of it, which can be used in ATP/EMTP, is explained at Fig.8b.

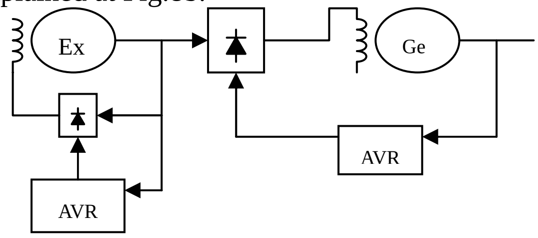

Fig.8a Prototype of excitation system of #2 generator

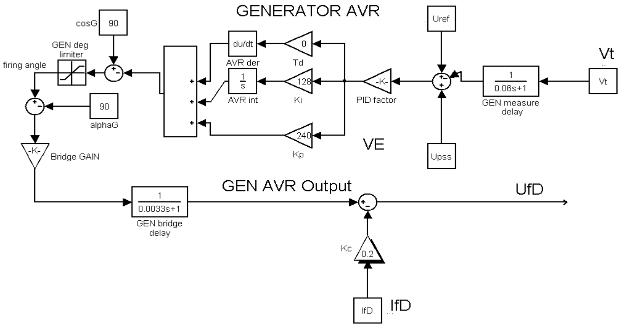

Fig.8b Excitation system model of #2 generator in transfer function form.

3.3 Test Results

Fig.9~Fig.12 show the simulation results. Although measurements got from two lines are not in phase, which has been explained at Section 2, the EMTP can also obtain compromise simulation results.

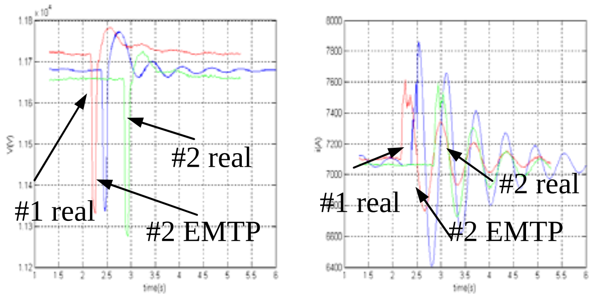

Fig.9 Terminal Voltage of generator #2 at Plant 1 (Phase A) Fig.10 stator Current of generator #2 at Plant 1 (Phase A)

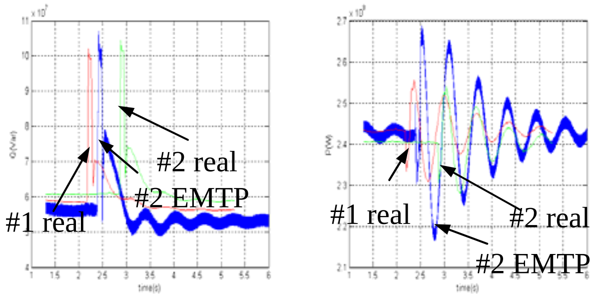

Fig.11 Reactive power of generator #2 at plant 1
Fig.12 Active power of generator #2 at plant 1

4 Results and Discussions

4.1 Influence on Neighboring Generators

In section 4.1, only the impact load at bus NGB is taken into consideration, as shown at Fig.13 and Fig.14. In Fig.15, when the load changes continually, the electrical-magnetic torque of the generator fluctuates correspondingly, which induces the vibration of the shaft. Furthermore, comparing the electrical –magnetic torque of the generator at Fig.15 with the electric-magnetic torque of excitor at Fig.16, they follow different vibration rules. So, the relative movement occurs between them, which lead to the shaft torsional vibration. Fig.17 shows the imbalance of the impact load causes the imbalance of the terminal voltages, which results in the harmonics on the system.

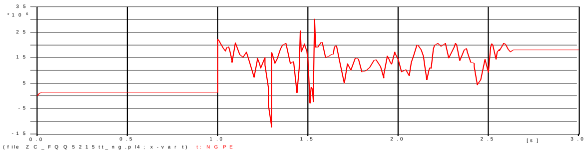

Fig.13 Active power at NGB

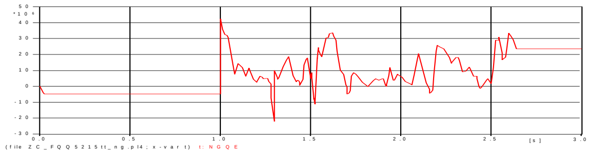

Fig.14 Reactive power at NGB

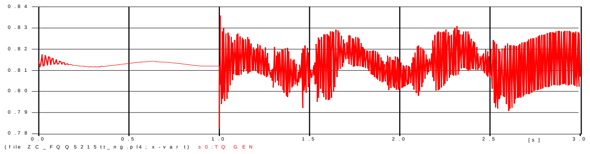

Fig.15 Electrical-magnetic torque of #2 generator at Plant 1

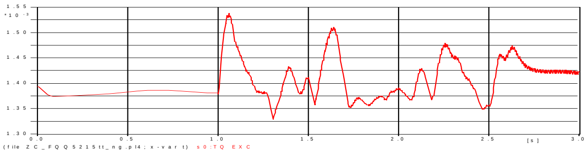

Fig.16 Electrical-magnetic torque of the excitor of #2 generator at Plant 1

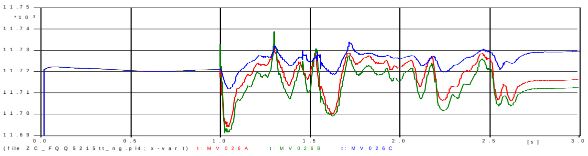

Fig.17 Terminal voltage RMS value of #2 generator

4.2 Influence of Network Structure

The test systems discussed here are shown at Fig.I and Fig.II in appendix, which demonstrate the structure change of this network. 15 impact loads are modeled as CCS and no CVS is considered. At Fig.I, Subnet 1 and Subnet 2 are connected by double PC-DSQ lines and one line from NR. At Fig.II, Subnet 1 and Subnet 2 are linked by double JB-DSQ lines, 500kV.

Table 1 Influence on plant of upward impacts

		Plant 1	Plant 2
Case 1	ΔU %	0.4542	0.3042
	ΔP (MW)	50.0070	11.0755
	ΔQ MVar	34.4419	7.9193
Case 2	ΔU %	0.4804	0.3065
	ΔP (MW)	54.8261	1.9748
	ΔQ MVar	60.6367	1.4391

Table 2 Influence on PCC of upward impacts

PCC	Case 1	Case 2
	ΔU %	ΔU %
LH(case 1) /CH(case 2)	1.5016	1.3037
PC	0.7180	1.2678

As shown at Table 1 and Table 2, the voltage change of bus PC increases. Comparing with that of case 1, the active power and the reactive power supplied by Plant 1, increase highly at case 2, whereas the active power and the reactive power supplied by Plant 2, decrease highly at case 2. The reason is that Plant 1 and Plant 2 share the impact load at Case 1, while Plant 1 supplies the impact load by itself at Case 2. When the system structure changed, the impact of EAFs and the like will be changed. The operators and planners should consider these changes and do further simulation research.

4.3 Simultaneity of EAFs

The test system here is shown at Fig.I at appendix. Downward impacts are considered. When joining points are close, Simultaneity of EAFs affects the generators nearby obviously. If they are far away from each other, it has little effect on the generators. When the impact loads occur at the same moment, the changes of the variables in care are not as big as the sum of all single impact load acting. Data at Table 3 ensure this conclusion. In fact, impact loads cause the change not only at generator power supplies, but also at the power flow. As a result, the impact acting on the PCC or the generator nearby is not to increase linearly. When the impacts occur simultaneously, the influence is less than the sum one by one. It results from the power flow redistribution. During some special situation, such as, overhaul, simultaneity of EAFs should be paid attention.

Table 3 Variables at nearby plants at different simultaneity

		NGB	SZJ	NGB +SZJ	ALL
Plant 1	ΔU %	0.4542	0.4541	0.4542	0.4542
	ΔP (MW)	14.0946	24.289	27.463	25.003
	ΔQ (MVar	19.3666	8.5224	14.564	17.220
	ΔU %	0.3043	0.3042	0.3042	0.3042

5 Conclusions

By means of field measurements, the impact models of electric arc furnaces (EAFs) are built and inserted into EMTP/ATP. Their influence on nearby generators is studied, including electromagnetic torque fluctuation and excitation system response. The results would give some positive advices to utility operators. The simultaneity of EAFs operating is also discussed. The worst effect of EAFs is concerned, especially when all EAFs start to work or stop almost simultaneously. Finally, it may be noted that, lots of EAFs may cause some damage to generators and should be paid much attention. In order to evaluate the impacts of existing or planned nonlinear loads, and select the connection points of new EAFs, this modeling method may be a good choice.

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Appendix

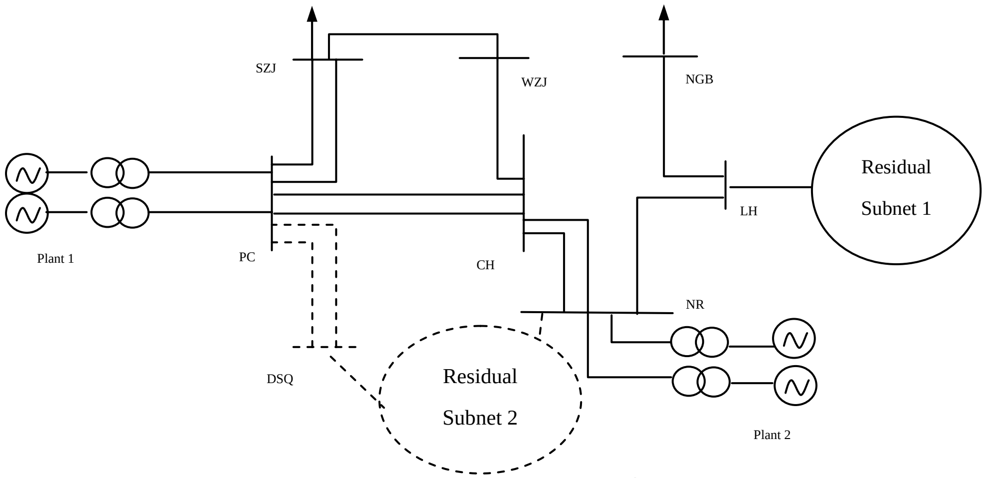

Fig.I Local network of case 1

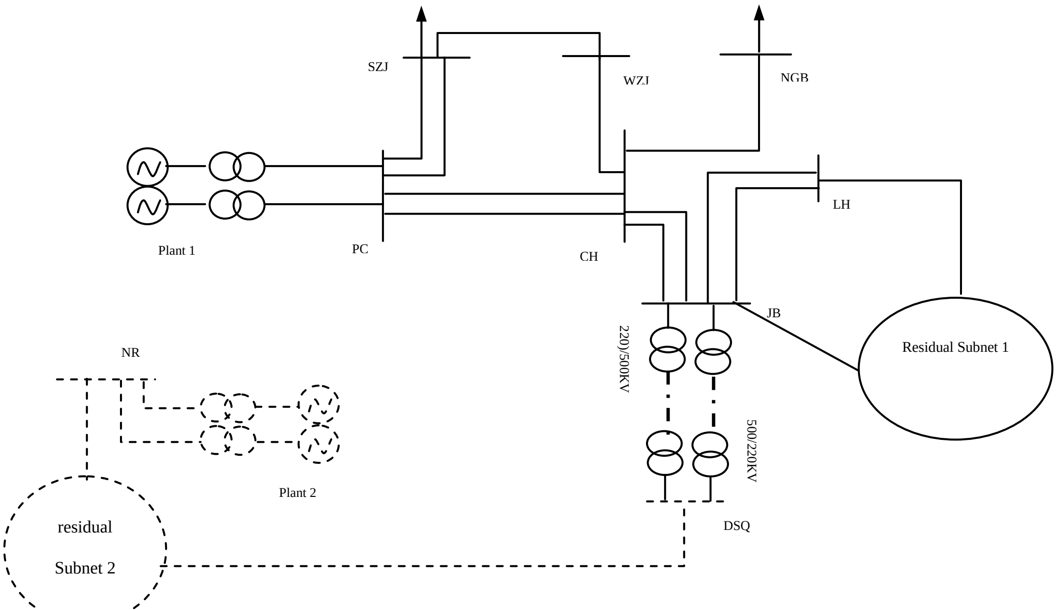

Fig.II Local network of case 2