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基于EMTP-ATP的变电站铁磁谐振计算与消谐措施研究

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摘要: 变电站发生单相接地故障后易引发电压互感器(TV)铁磁谐振,导致TV熔丝频繁熔断,影响电力系统安全运行。为研究变电站铁磁谐振基本规律及影响因素,文中基于EMTP-ATP电磁暂态仿真软件,考虑了TV铁心的非线性特性,建立了某35 kV变电站铁磁谐振计算的分布参数模型,分析了变电站铁磁谐振的产生原因,并提出了抑制措施。研究表明:单相接地消失时刻决定了TV是否会激发铁磁谐振,若接地消失时非故障相电压为瞬时最大值,则TV将发生最严重的铁磁谐振。变电站消谐措施应优选消弧线圈与消谐器,其次是在开口三角绕组投入阻尼电阻。消弧线圈投入后,使得接地消失时刻TV三相电流降低至远小于其额定电流,从根本上避免了TV熔断器熔断;35 kV侧加装消弧线圈对于抑制10 kV侧TV铁磁谐振并无作用。安装消谐器时,在保证抑制铁磁谐振的同时,应考虑TV三相电流不能超过其额定值,避免熔丝熔断。TV开口三角绕组投入阻尼电阻值越小,对铁磁谐振的抑制效果越好,但TV三相电流越大,易烧毁熔断器;应准确判断接地消失时刻,精准投入阻尼电阻。

关键词: EMTP-ATP; 铁磁谐振; 消谐措施; 消弧线圈; 消谐器; 阻尼电阻

Researches on Ferromagnetic Resonance Calculation and Harmonic Elimination Measures in Substation Based on EMTP-ATP

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Abstract: After the single-phase grounding fault occurs in the substation, the ferromagnetic resonance of the voltage transformer (TV) is easily triggered, which causes the frequent fusing of the TV fuse and influences the safe operation of the power system. For researching the essential laws and influence factors of ferromagnetic resonance in substation, based on the EMTP-ATP electromagnetic transient simulation software and considering the nonlinear characteristics of TV core, a distributed parameter model of ferromagnetic resonance calculation in a 35 kV substation is established. The cause of ferromagnetic resonance in substation is analyzed, and the restraining measures are put forward. The research shows that the single phase ground disappearance time determines whether TV will excite ferromagnetic resonance. If the voltage of the non fault phase is instantaneous maximum, the most severe ferromagnetic resonance of TV will occur. The arc suppression coil and the harmonic eliminator should be preferred in the substation harmonic elimination measures, and the second is to put the damping resistor in the open triangular winding. After the arc suppression coil is put into operation, the TV three-phase current is reduced to far less than its rated current at the time of earth disappearance, which fundamentally avoids the fusing of TV fuse. 35 kV side adding arc suppression coil as no effect on suppressing 10 kV ferromagnetic resonance. When installing the harmonic eliminator, the TV three phase current should not exceed its rated value to avoid fuse while ensuring the suppression of ferromagnetic resonance. The smaller the input resistance value of TV open delta winding is, the better the inhibition effect for ferromagnetic resonance. But the larger the three-phase current of TV is, the easier it will burn the fuse. The time of the earth's disappearance should be accurately judged, and the damping resistor can be switched accurately.

Key words: EMTP-ATP; ferromagnetic resonance; harmonic elimination measures; arc suppression coil; harmonic eliminator; damping resistor

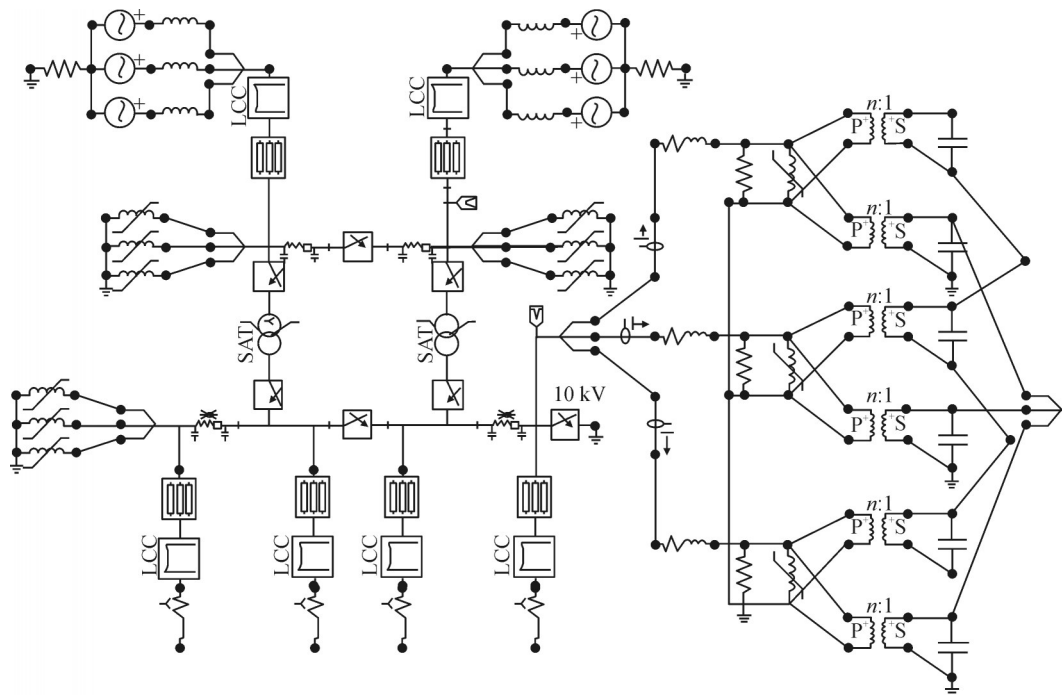


图3 35 kV变电站铁磁谐振仿真计算模型

Fig. 3 Simulation and calculation model for ferromagnetic resonance in 35 kV substation

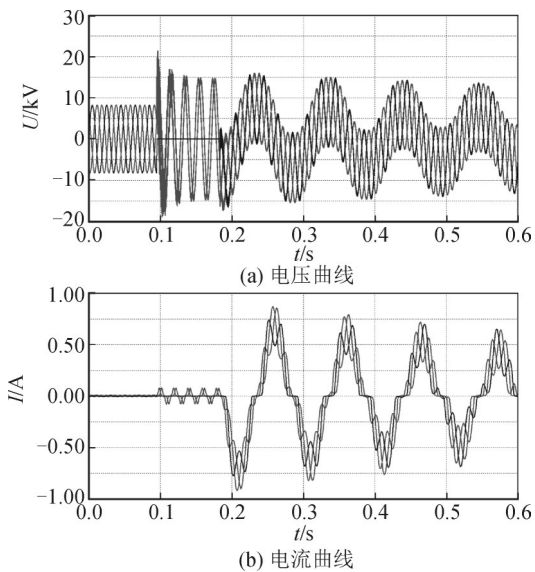


图4 单相接地后TV三相电压电流(0.1837 s接地消失)

Fig. 4 The three phase voltages and currents of TV after single-phase grounding (grounding disappears in 0.1837 s)

(B、C相电压极性相反,幅值相等)时,A相接地消失,此时系统发生频率为5.2 Hz的分频谐振,谐振电压最大值为-1.28 p.u.(A相)。由图5(b)可见,当接地故障消失后,TV的A、B、C三相电流增大,幅值最大值为0.182 A,未超过TV熔断器的额定电流。

图4、5表明,单相接地消失时刻对于是否激发TV铁磁谐振起决定作用。当系统发生单相接地时,非故障相电压升高;故障消失时,非故障相在接地期间储存的大量电荷需经TV中性点释放掉。接地消失时,非故障相的瞬时电压决定了是否发生铁磁谐振。若

接地消失时非故障相电压为瞬时最大值,则TV将流过幅值很高的电流,导致TV铁心饱和,励磁电抗急剧减小。若与线路等效电容匹配,则会发生严重的铁磁谐振,如图4所示。若接地消失时刻非故障相电压幅值较小,则流经TV的电流较小,TV不会出现严重饱和,也不会发生严重的铁磁谐振,如图5所示。

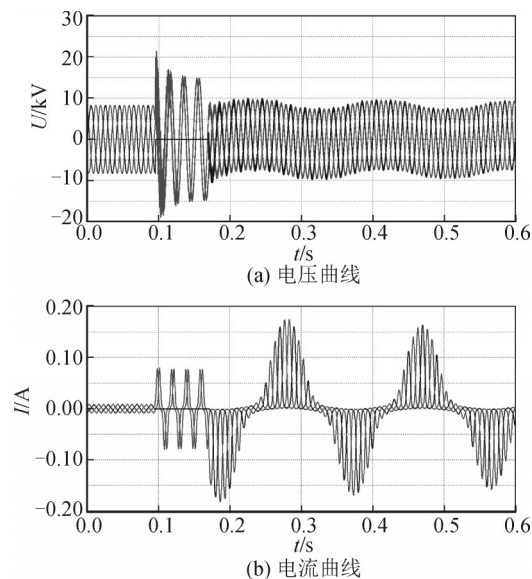


图5 单相接地后TV三相电压电流(0.17 s接地消失)

Fig. 5 The three phase voltages and currents of TV after single-phase grounding (grounding disappears in 0.17 s)

3.2 铁磁谐振抑制措施

抑制变电站铁磁谐振的常见措施包含:①在TV中性点加装消谐器(即非线性电阻);②在TV开口三角绕组加阻尼电阻;③在变压器中性点加装消弧线

圈;④在变压器中性点加装大电阻;⑤选取饱和特性点高,励磁特性好的TV;⑥合理改善无功设备的投切方式,避免频繁投入和断开等。以下将分别讨论上述措施的可行性及效果。

1)TV中性点加装消谐器。两种不同的10 kV消谐器伏—安特性曲线见图6。将A、B两种消谐器分别接至图3中TV的中性点,仿真计算了两种情况下TV三相电压电流曲线见图7、8。

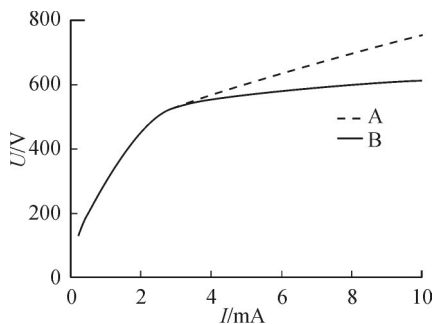


图6 两种消谐器伏—安特性曲线

Fig. 6 The V-A curves of two resonance eliminators

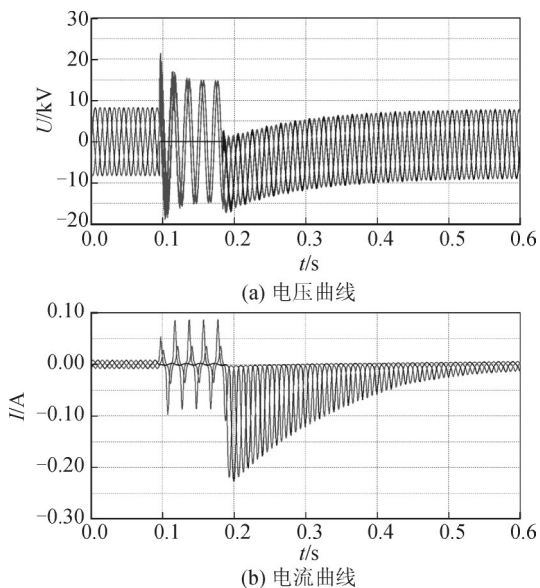


图7 TV中性点加装消谐器A后三相电压电流

Fig. 7 The three phase voltages and currents of TV after installing neutral point resonance eliminator A

对比图7、8的 $U-I$ 曲线可见,消谐器A将谐振过电压抑制到正常值需要0.3 s,而消谐器B则仅需要不到0.1 s,消谐器B抑制过电压的效果优于消谐器A。这可从图6中A、B两种消谐器的 $U-I$ 曲线得到解释。在 $U-I$ 曲线图中,当电流大于3 mA后,消谐器B的 $U-I$ 曲线的斜率小于消谐器A,即 $I > 3$ mA后,消谐器B的等效阻抗小于消谐器A。非故障相母线上的残余电荷可更快地经消谐器B释放掉,故消谐器B的过电压抑制效果优于消谐器A。但是,加装消谐器B后,TV三相谐振电流最大值为0.453 A,大于加装消谐器A的谐振电流0.226 A。因此,在选

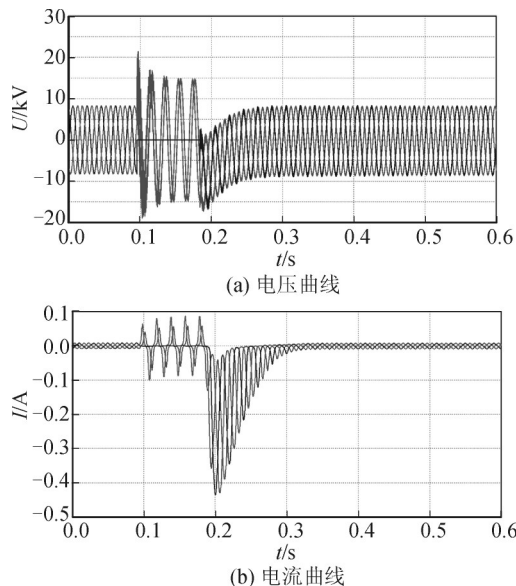


图8 TV中性点加装消谐器B后三相电压电流

Fig. 8 The three phase voltages and currents of TV after installing neutral point resonance eliminator B

装消谐器时,在保证抑制谐振效果的同时,应考虑TV三相电流不能超过其额定电流,避免熔丝熔断。

2)TV开口三角绕组加装阻尼电阻。故障消失时刻,在TV开口三角绕组投入 $5\ \Omega$ 和 $2\ \Omega$ 阻尼电阻后TV三相电压电流曲线见图9、10。从图9、10可见,阻尼电阻为 $2\ \Omega$ 时的谐振抑制效果优于阻尼电阻为 $5\ \Omega$ 时的效果,即阻尼电阻越小,对TV铁磁谐振的抑制效果越好。当阻尼电阻趋近于0时,相当于TV二次直接接地,更容易释放故障相上的残余电荷,抑制效果越好。但阻尼电阻值不可过小,电阻值过小,TV三相电流幅值增大,可能超过TV额定电流(如图10(b)电流幅值达1.36 A),易引起高压熔丝熔断。

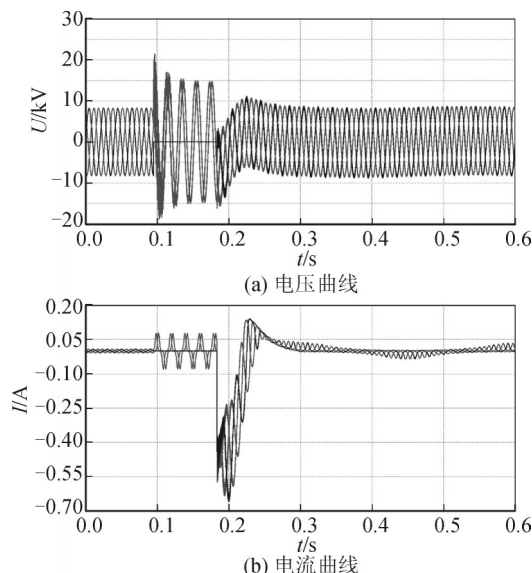


图9 TV开口三角加 $5\ \Omega$ 阻尼电阻后三相电压电流
Fig. 9 The three phase voltages and currents after installing $5\ \Omega$ damping resistor between open triangle winding

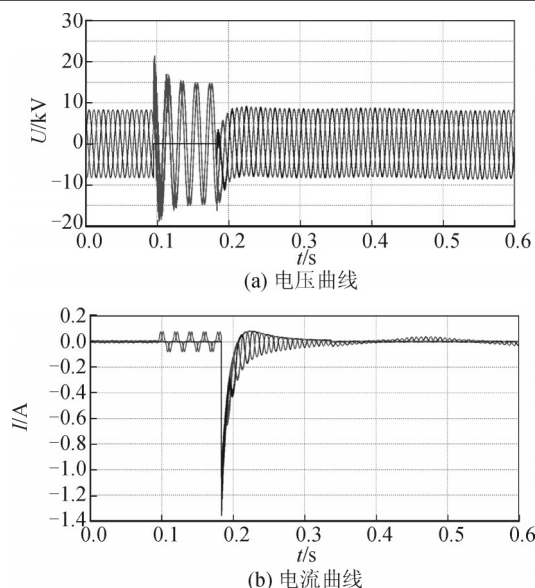


图10 TV开口三角加 $2\ \Omega$ 阻尼电阻后三相电压电流
Fig. 10 The three phase voltages and currents after installing $2\ \Omega$ damping resistor between open triangle windings

TV开口三角绕组阻尼电阻的投入时间对其三相电流大小有一定影响。TV开口三角绕组直接接入 $5\ \Omega$ 阻尼电阻后TV三相电流见图11。由图11可见,此时TV高压绕组最大电流为 $0.73\ \text{A}$,大于图9(b)中的最大电流值,且电流持续时间更长,容易引起TV高压熔丝熔断。因此,应准确判断接地消失时刻,精准投入阻尼电阻。

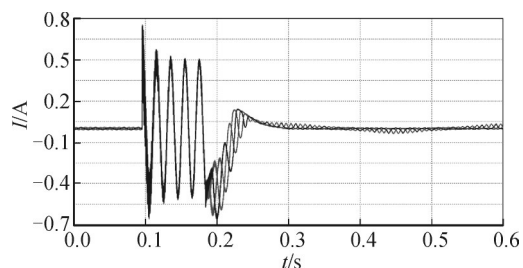


图11 TV开口三角持续投入 $5\ \Omega$ 阻尼电阻后三相电流
Fig. 11 The three phase voltages and currents after continued investing $5\ \Omega$ damping resistor between open triangle windings

3)加装消弧线圈。在 $10\ \text{kV}$ 母线侧接地变压器中性点加装消弧线圈后的电压电流曲线见图12。由图12(a)可见,加装消弧线圈后,TV三相过电压得到迅速抑制,TV未出现铁磁谐振现象。由图12(b)可见,三相电流幅值为 $0.079\ \text{A}$,远小于TV高压熔断器的额定电流。

$10\ \text{kV}$ 母线A相接地,在变压器 $35\ \text{kV}$ 侧中性点加装消弧线圈后, $10\ \text{kV}$ TV三相电压曲线见图13。从图13可见, $35\ \text{kV}$ 侧加装消弧线圈对于抑制 $10\ \text{kV}$ 侧TV铁磁谐振并无作用。

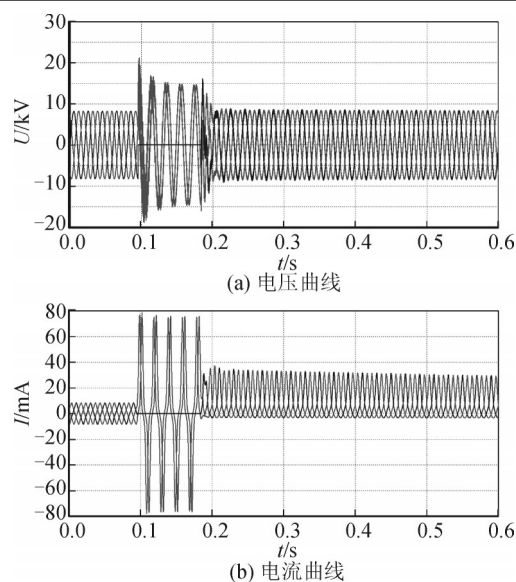


图12 $10\ \text{kV}$ 侧加消弧线圈后TV三相电压电流
Fig. 12 The three phase voltages and currents of TV after installing extinction coil in $10\ \text{kV}$ system

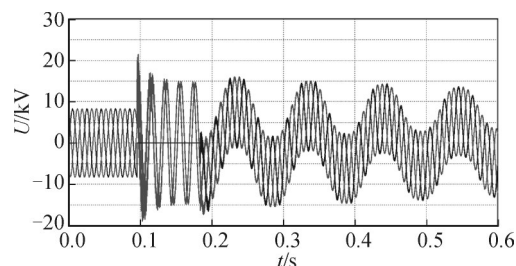


图13 $35\ \text{kV}$ 侧加装消弧线圈后TV三相电压
Fig. 13 The three phase voltages and currents of TV after installing extinction coil in $35\ \text{kV}$ system

4)主变中性点加装大电阻。主变中性点经大电阻接地后TV三相电压见图14。从图14可见, $35\ \text{kV}$ 主变高压侧中性点经大电阻接地后,对抑制 $35\ \text{kV}$ 母线TV铁磁谐振有明显作用。随接地电阻值减小,TV铁磁谐振减弱。但接地电阻不应过小,否则会明显改变 $35\ \text{kV}$ 系统的运行方式。

4 结论

1)单相接地消失时刻对于是否激发TV铁磁谐振起决定作用。若接地消失时非故障相电压为瞬时最大值,则TV将发生最严重的铁磁谐振。

2)变电站消除铁磁谐振的措施优选消弧线圈与消谐器,其次是在TV开口三角绕组投入阻尼电阻。

3)消弧线圈投入后,使得接地消失时刻TV三相电流降低至远小于其额定电流,从根本上避免了TV熔断器熔断。 $35\ \text{kV}$ 侧加装消弧线圈对于抑制 $10\ \text{kV}$ 侧TV铁磁谐振并无作用。

4)选装消谐器时,在保证抑制铁磁谐振效果的同时,应考虑TV三相电流不能超过其额定电流,避

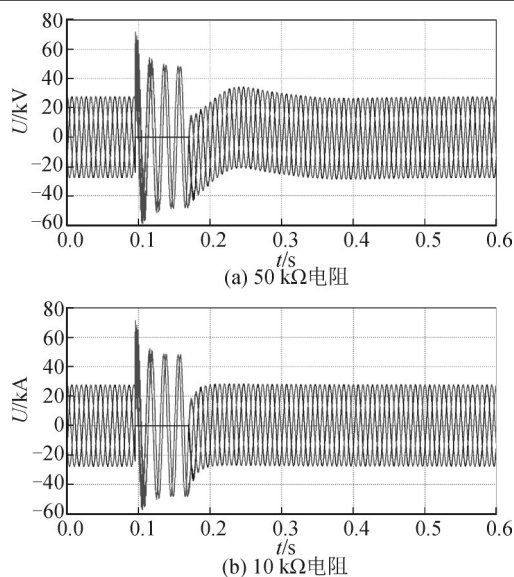


图14 35 kV变压器中性点加大电阻后TV三相电压
Fig. 14 The three phase voltages and currents of TV after installing large resistor in neutral point of 35 kV transformer

免熔丝熔断。

5)TV开口三角绕组投入阻尼电阻值越小,对铁磁谐振的抑制效果越好,但TV三相电流越大,易烧毁熔断器。同时,应准确判断接地消失时刻,精准投入阻尼电阻。

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