EXPONENTIALLY CHANGING TRANSIENTS AND RELAYING APPLICATION CONSIDERATION

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1. Introduction

A **DC trip circuit** is merely a series RL circuit switching from one condition to another by a status change of a protective relay contact. There is a transitional period during which the trip circuit current changes from zero to a new value. During the transition period the trip circuit current adjusts from its initial value of zero to the final steady-state value V/R in the form of exponential rise with a time constant of L/R.

It appears that many utilities use 3-cycle circuit breakers and circuit breaker 52a contacts open the DC trip circuits in less than 3 cycles. Therefore, the trip circuit currents rarely reach the steady state. For example, a DC trip circuit in Figure 1 - DC Trip Circuit with Reclose Initiating Relay had only 350 milliamps at the opening of 52a contact even though the manufacturer's specifications indicated a rated trip coil current of 2.8 amps. This 350-milliamp was not high enough to fully energize a 2.5-amp current-operated auxiliary (reclose initiating) relay.

Basically, a half of this paper emphasizes that control circuit designers and relay technicians should understand DC transients in trip circuits to ensure proper operation of trip circuits and also to adequately size DC batteries and contacts. A poorly designed trip circuit may not drop an electrically operated target because of the low, exponentially rising DC circuit current. This paper also emphasizes the importance of complete functional testing of trip circuits (trip testing) instead of the traditional bench testing with steady-state current injection.

In general, AC synchronous generator impedance is the subtransient reactance at the moment of a fault and it eventually changes to the steady-state synchronous reactance. Because of this transitional nature of generator impedance, the fault current from a synchronous generator decays exponentially and reaches the steady-state rated generator current within several seconds. A curve representing this fault current transition is called the **generator fault current decrement curve** or the **decrement curve**.

Adequate operation of many overcurrent relays strictly relies on the high fault current availability, but high fault currents may not be available only a second after the fault inception. In addition, an overcurrent relay with an operating characteristic curve above the decrement curve on the time-current coordination (TCC) sheet will never operate reliably as shown in Figure 2 – Generator Decrement Curve. Therefore, the remaining half of this paper emphasizes the importance of properly using decrement curves in overcurrent relay coordination, especially for overcurrent relays at or near generating stations.

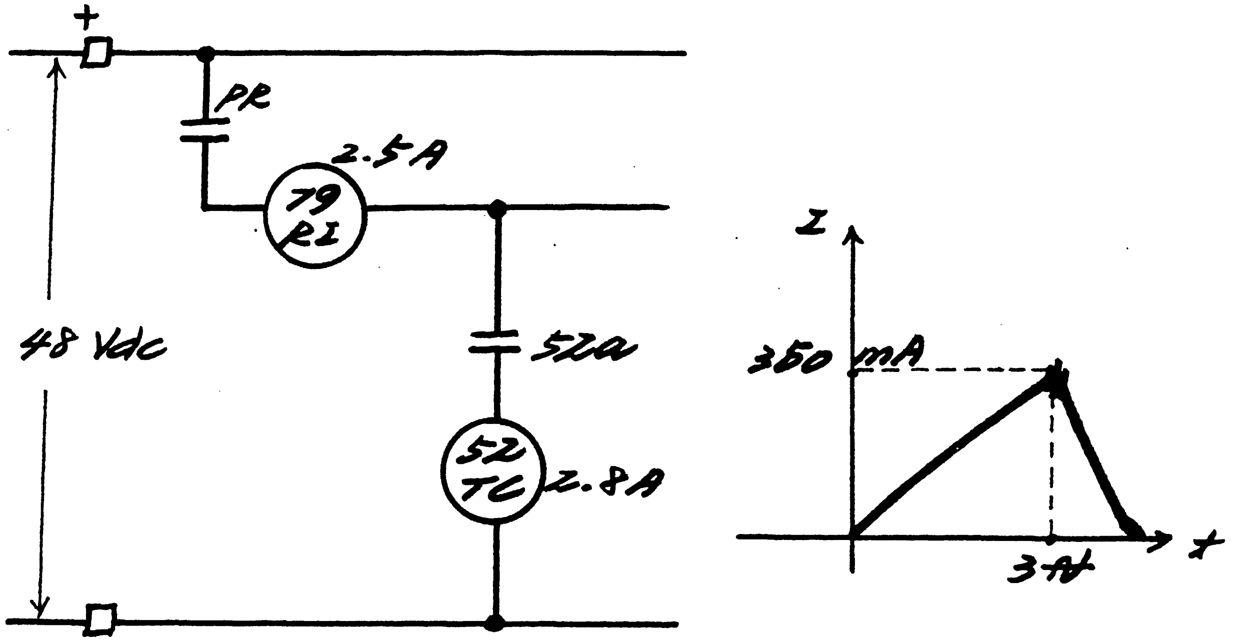

Fig. 1. DC Trip Circuit with Reclose Initiating Relay

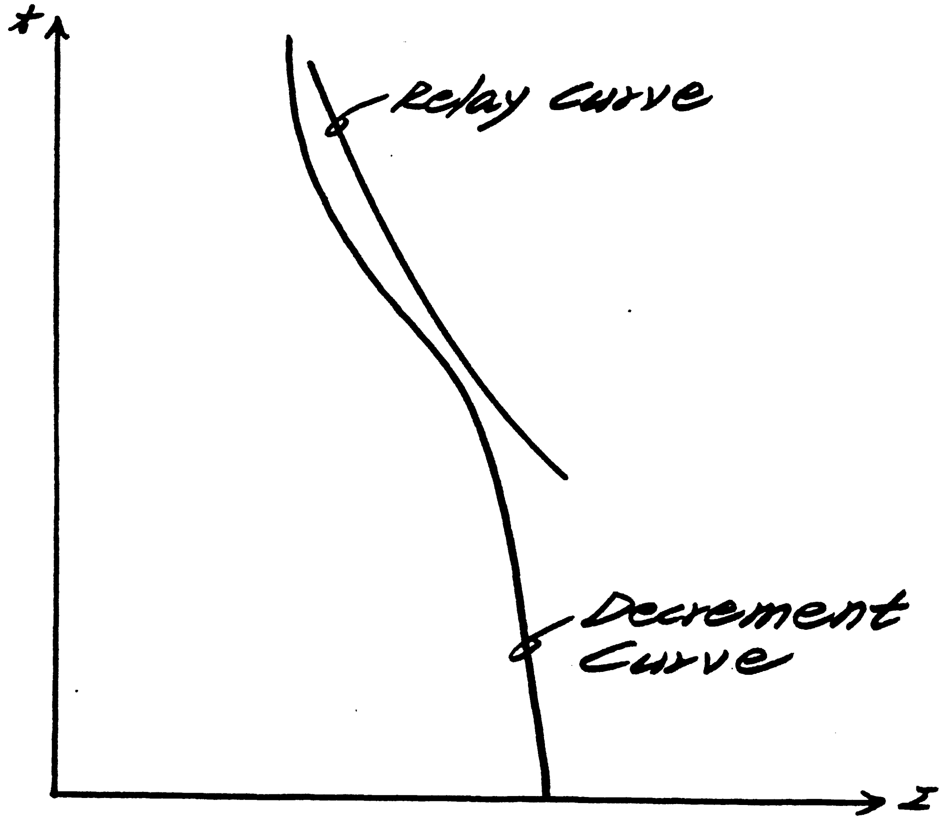

Fig. 2. Generator Decrement Curve

2. Exponentially Rising DC Trip Circuit Transients

2.1 Switching Transients in Series RL Circuits

A simple series RL circuit shown in Figure 3 – Series RL Circuit has a DC supply voltage V applied when the switch is closed. The current is

$$i = \frac{V}{R}(1 - e^{-(R/L)t})$$

The plot shows a transition period during which the current adjusts from its initial value of zero to the final steady-state value V/R with a time constant of L/R. The resistor voltage transient is an exponential rise with the same time constant as the current, while the voltage across the inductance is an exponential decay.

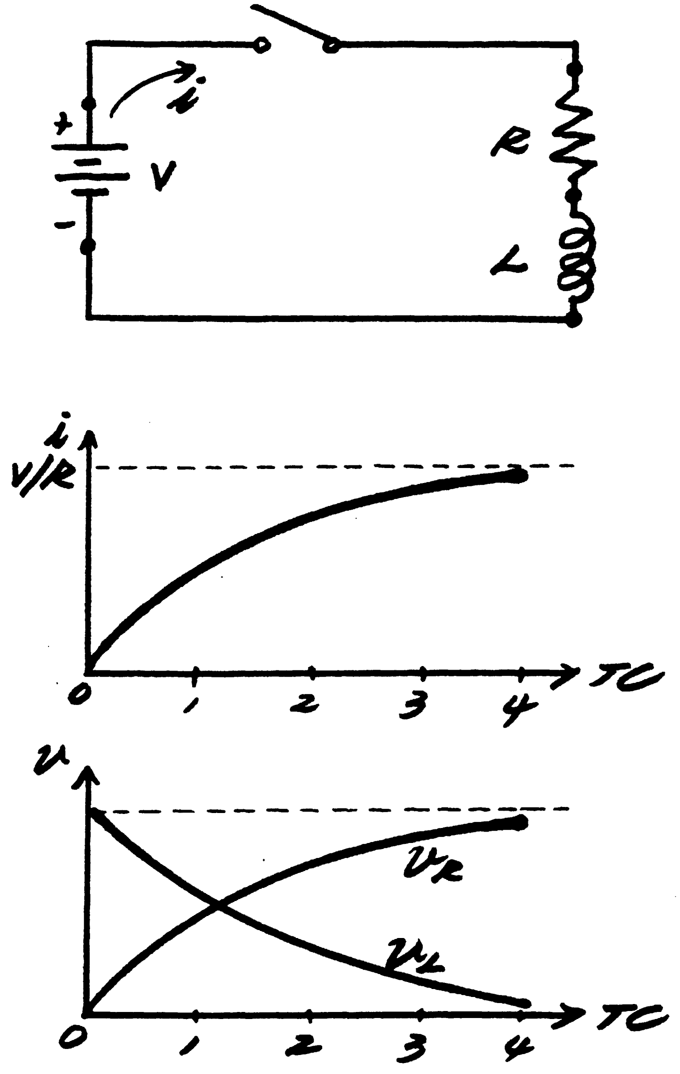

Fig. 3. Series RL Circuit

2.2 Switching Transients in DC Control Circuits

A DC trip circuit is merely a series RL circuit switching from one condition to another by a status change of a protective relay contact as said previously. The following Figure 4 – Small Trip Coil Current shows only 350-milliamp current flow at the opening of 52a contact even though the manufacturer's specifications indicated a rated trip coil current of 2.8 amps. This 350-milliamp current was not high enough to fully energize a 2.5-amp current-operated reclose initiating relay. This problem was corrected by installing a 20-ohm 25-watt resistor across the trip coil.

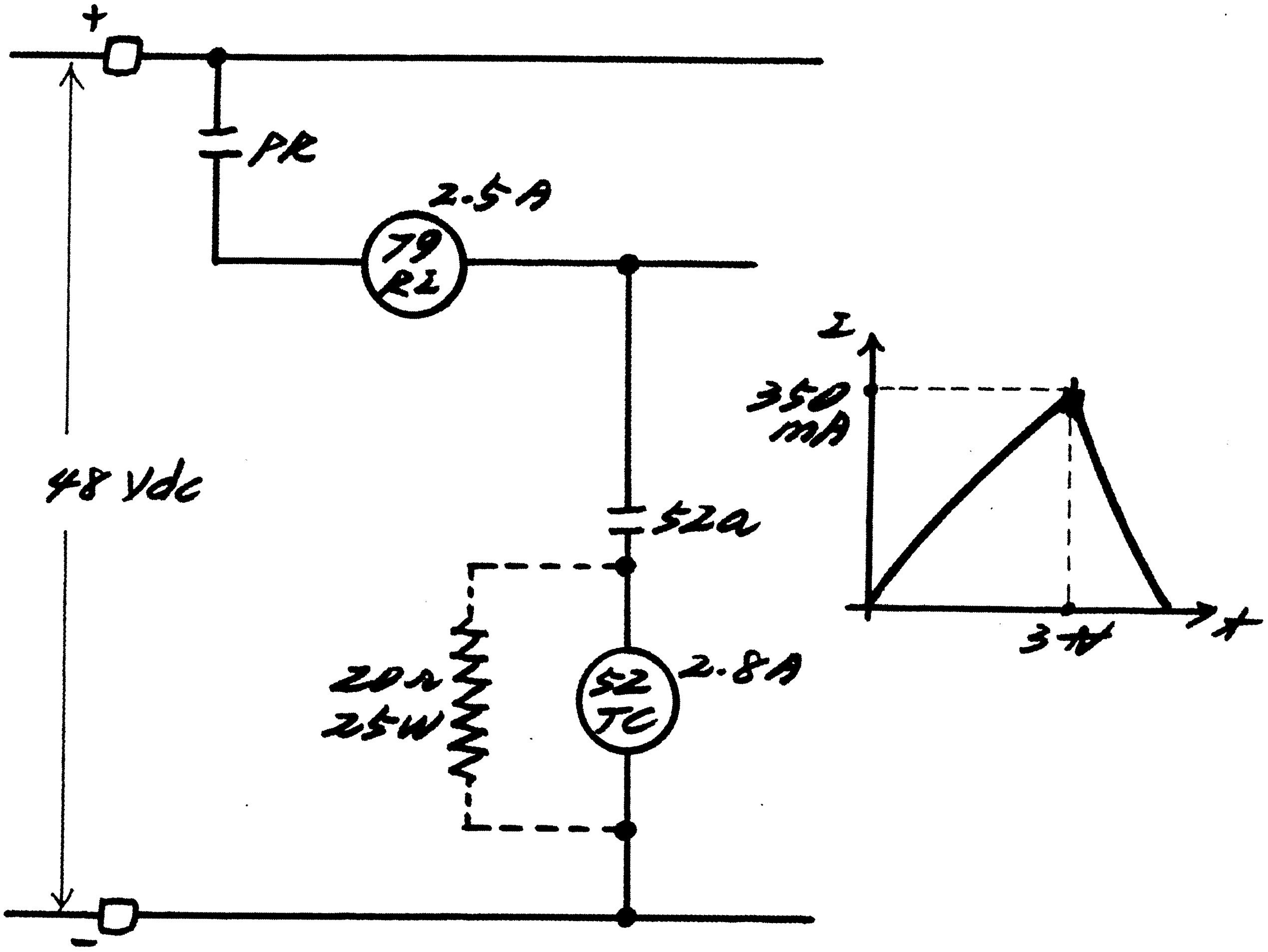

Fig. 4. Small Trip Coil Current

Lockout Relay Coil Current - Electrically, DC lockout relay circuit is very similar to the DC trip circuit. Figure 5 - Lockout Relay Coil Current shows the rated 4.5-amp current flow at the opening of coil cutoff contact, but it takes only 6.1 milliseconds from the current zero to the rated 4.5 amps. This exponentially rising transient current may not be sufficient to drop an electrically operated target, so it is customary to install an adequately-sized target-dropping resistor across the lockout coil. This resistor installation will ensure positive target dropping, but slow the lockout relay operation.

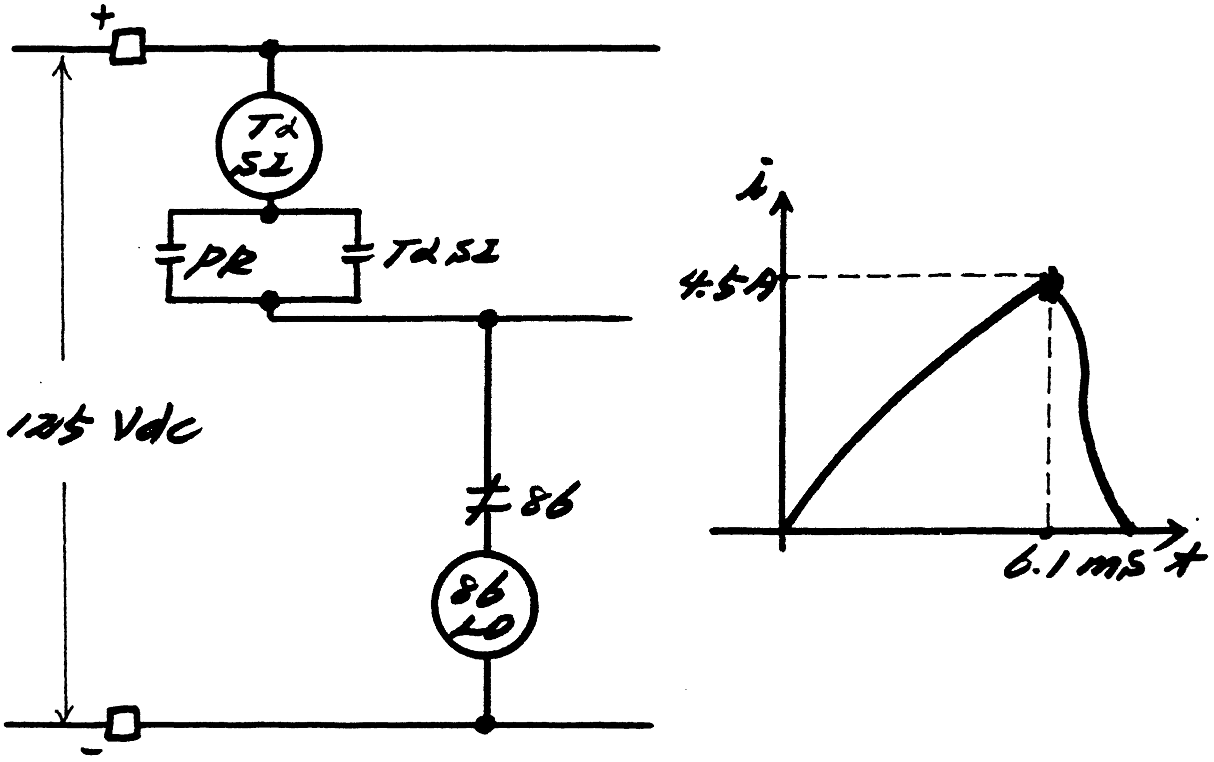

Fig. 5. Lockout Relay Coil Current

230-kV Circuit Breaker Trip Coil Currents - Figure 6 – 230-kV Circuit Breaker Trip Coil Currents illustrates two different trip coil current waveforms: The first waveform represents a trip coil current of 230-kV 3-cycle oil circuit breaker and the second one represents a trip coil current of 230-kV 3-cycle SF6 gas circuit breaker. Both trip coils are rated at 8.5 amps. It is quite interesting to see the difference in operating times and wave shapes: One with 42.1 milliseconds and the other with only 14.1 milliseconds.

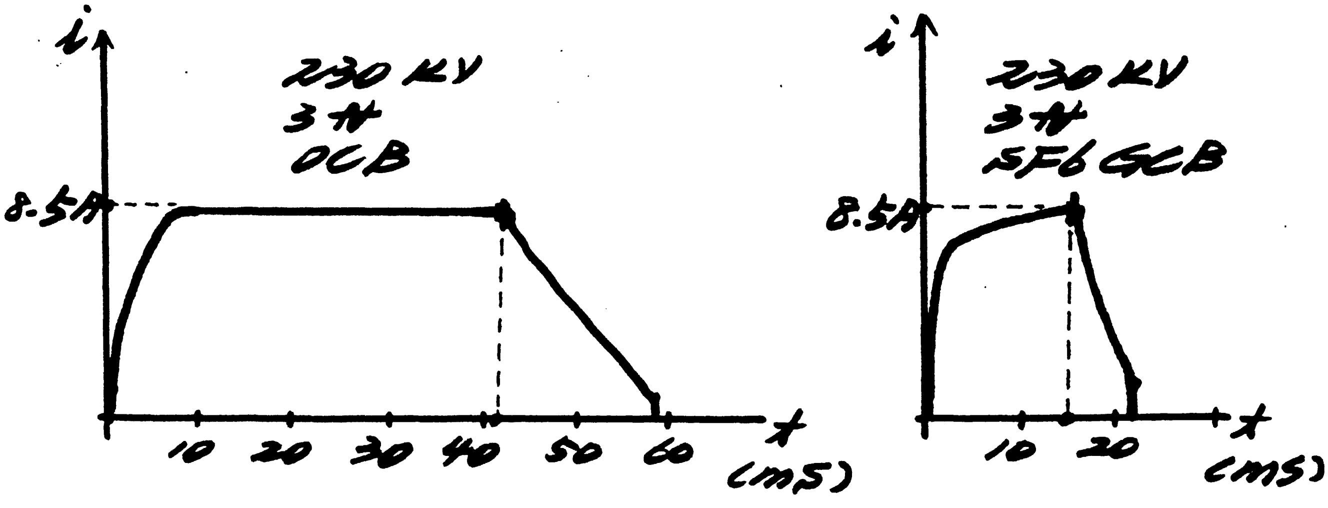

Fig. 6. 230-kV Circuit Breaker Trip Coil Currents

2.3 Impacts to Control Circuit Design and Testing

All DC control circuit current waveforms presented above are transients in nature and these transients last only for the breaker (or relay) operating periods. This transient nature of DC control circuit coil currents brings up several issues primarily related to control circuit design and testing. Some of these issues are:

Auxiliary Relay Selection – As shown in Figure 4 – Small Trip Coil Current, there was not anything wrong with the control circuit designer's design, but the reclose initiating relay could not operate because there was not sufficient current flow through the reclose initiating relay coil. The designer designed the control circuit based on the manufacturer's current ratings as any other control circuit designers would. Some of the following measures may ease the auxiliary relay selection problem:

- Select sensitive relays as we would select a 2-amp seal-in & target tap for a 13-amp trip coil normally. For example, select a reclose initiating relay with a 0.3-amp operating coil for the 2.8-amp trip coil in Figure 4.
- Install a target-dropping resistor across the trip coil to ensure positive target dropping. It is a very easy fix, but this resistor installation may slow the breaker (or lockout relay) operation.
- Use modern microprocessor-based relays with many programmable input/output contacts. This may eliminate the need for auxiliary or interposing relays.

Coil Current Ratings – After I reviewed several coil ratings and coil current waveforms presented in this paper, it has been quite difficult to understand what the coil ratings really mean, especially the 2.8-amp coil rating and actual operation at 0.35 amp.

Validity of Bench Testing – For a target operation test, it is not uncommon for a relay technician to test relays for target dropping on his/her relay test bench. It is also not uncommon to see relay operation without target dropping, so it is very important for relay technicians to conduct complete functional testing of trip circuits (trip testing) instead of the traditional bench testing with steady-state current injection.

Contact Ratings – All contacts shown in this paper were required to interrupt (or subjected to interrupting) transients. It will be interesting to know why the contacts are required to interrupt steady-state rated coil currents because they will never interrupt the steady-state rated coil currents.

3. Exponentially Decaying Generator Fault Current

3.1 Generator Reactances and Time Constants

For synchronous generators, there are more reactances and time constants than we would like to remember. Fortunately, the following six parameters are all we need in order to construct simple generator decrement curves (More detailed information can be found in many references, especially in Edward Wilson Kimbark's Power System Stability: Synchronous Machines.):

- Xd – Direct-axis synchronous reactance
- Xd' – Direct-axis transient reactance
- Xd" – Direct-axis subtransient reactance
- Td' – Direct-axis transient short-circuit time constant
- Td" – Direct-axis subtransient short-circuit time constant
- Ta – Armature short-circuit time constant

Direct-Axis Transient Reactance, Xd' - Figure 7 – Flux Paths for Various Reactances of A Salient-Pole Synchronous Machine illustrates flux paths for Xd, Xd', and Xd". Abrupt application of high armature current (such as high fault current) causes the sudden appearance of a m.m.f. opposite each field pole, tending to establish flux through the pole core. Such flux would link the field winding and is opposed by induced field current, tending to maintain the flux linkage of the field winding constant at a zero value. By the theorem of constant flux linkage, at the instant immediately after application of the armature current the field linkage is still zero. Therefore, the only flux that can be established immediately is the flux that does not link the field winding but rather passes through low-permeance leakage paths, largely in air, as shown in Figure 7. Under these conditions the flux per ampere is small and the reactance is defined as the direct-axis transient reactance, Xd'.

Direct-Axis Subtransient Reactance, Xd" - If high armature currents are suddenly applied in such time when the crest of the rotating m.m.f wave is in line with the direct axis of the rotor, then transient currents are induced in the additional direct-axis rotor circuits (such as damper windings and field collars) as well as in the main field winding. These transient currents oppose the armature m.m.f. and initially they are strong enough to keep the flux linkage of every rotor circuit constant at a zero value. Consequently, the flux set up by the armature current is initially forced into leakage paths of smaller cross-sectional area and lower permeance. Under these conditions the flux per ampere is extremely small and the reactance is defined as the direct-axis subtransient reactance, Xd".

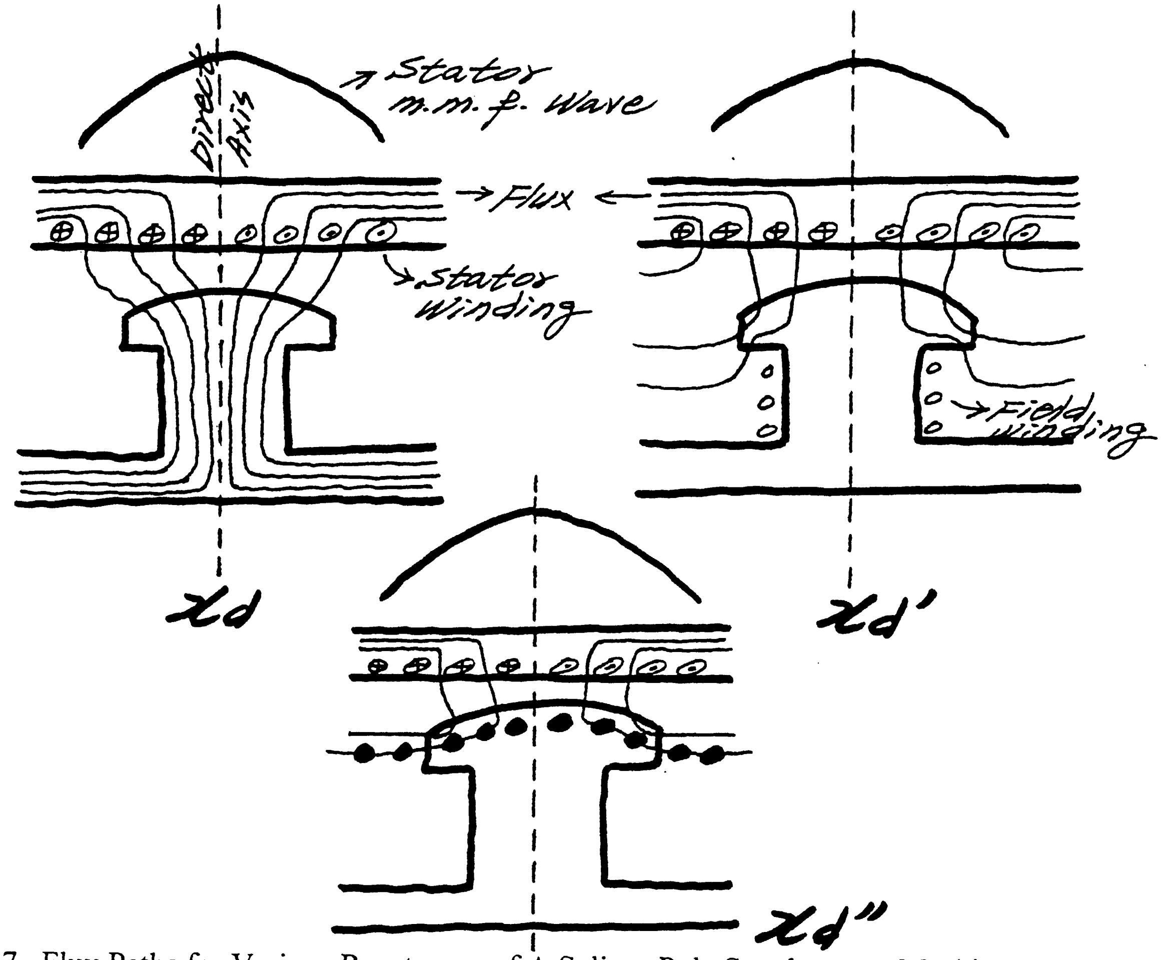

Fig. 7. Flux Paths for Various Reactances of A Salient-Pole Synchronous Machine

Effect of Damper Winding – Damper windings do not affect transient reactances but reduce subtransient reactance values significantly.

3.2 How to Construct Generator Fault Decrement Curves?

Fault current from a synchronous generator decays exponentially and eventually reaches the steady-state rated generator current. A curve representing this fault current transition is called a fault decrement curve. The amplitude of the AC component of short-circuit fault current (or armature current) may be written in terms of reactances as

$$I_{ac} = E\left[\frac{1}{x_d} + \left(\frac{1}{x_d'} - \frac{1}{x_d}\right)e^{-t/T_d'} + \left(\frac{1}{x_d''} - \frac{1}{x_d'}\right)e^{-t/T_d''}\right]$$

where E is the open-circuit voltage of an unsaturated machine. This highest fault current value is normally used in figuring the required short-time momentary ratings of generator circuit breakers, but only the AC component of the highest fault current is used for overcurrent device coordination as further explained later.

The DC component of armature current is given by

$$I_{dc} = \frac{\sqrt{2} E \cos \alpha}{X_d''} e^{-t/T_a}$$

The greatest possible initial effective value of fault (or armature) current, obtained with a fully offset wave, is composed of an AC component and a DC component.

$$I_{ac,max} = \frac{E}{X_d''}$$

$$I_{dc,max} = \frac{\sqrt{2} E}{X_d''}$$

$$I_{max} = \sqrt{I_{ac,max}^2 + I_{dc,max}^2}$$
$$= \frac{\sqrt{3} E}{X_d''}$$

Manufacturers' Decrement Curves - The following Figure 8 illustrates two sample decrement curves supplied by generator manufacturers.

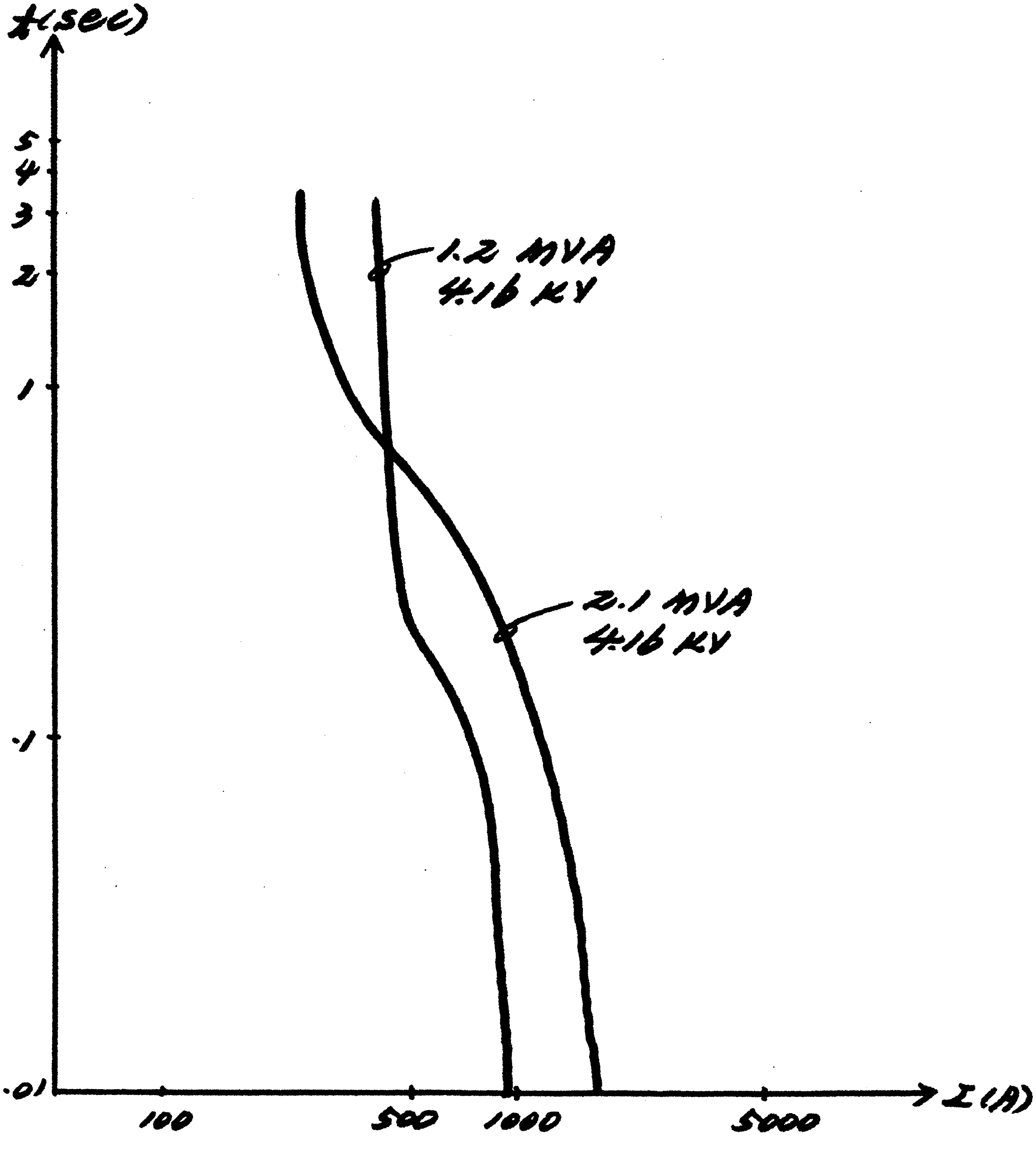

Fig. 8. Sample Decrement Curves (supplied by generator manufacturers)

Effect of Automatic Voltage Regulation and Loading – Effect of automatic voltage regulation (excitation system) is best illustrated in Figure 9 – Effect of Automatic Voltage Regulation and Loading. It is very important to recognize that automatic voltage regulation tends to increase the fault current amplitude and also tends to slow the exponential decaying. With automatic voltage regulation in service, both fault voltages and fault currents are dynamic. Therefore, all relays including overcurrent relays and distance relays located near the generator bus are subject to less-than-satisfactory performance.

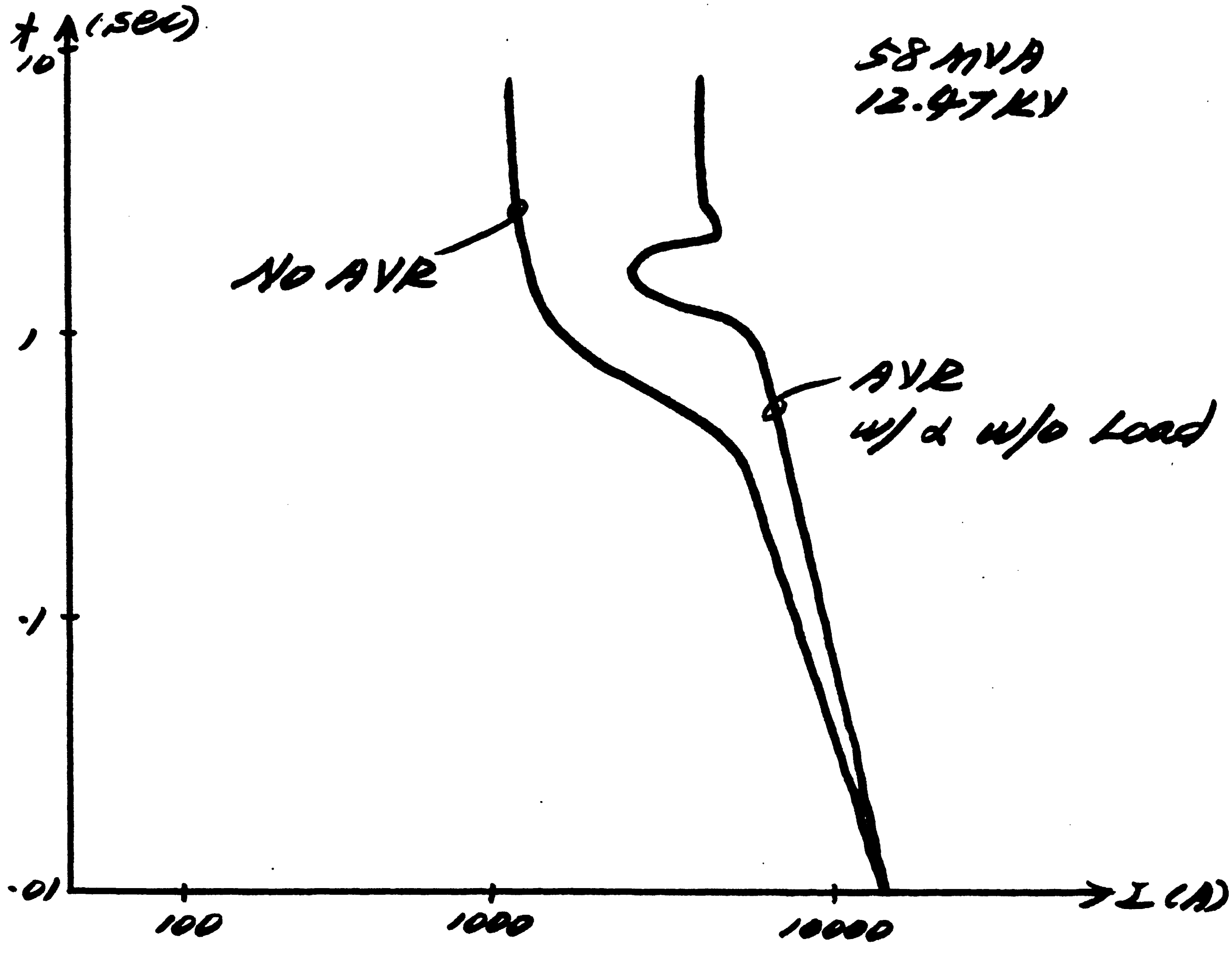

Fig. 9. Effect of Automatic Voltage Regulation and Loading

Effect of Fault Types – In general, fault types (3-phase fault, line-to-line fault, and single-line-to-ground fault) affect the direct-axis transient time constant. The line-to-line short circuit transient time constant is approximately 1.5 x Xd' and the single-line-to-ground short-circuit transient time constant is approximately 2 x Xd'. Therefore, slower (slower than exponential decaying for 3-phase short-circuit currents) exponential decaying is expected for both line-to-line and single-line-to-ground faults.

Effect of Residual Flux – Residual flux creates DC offset and the algebraic sum of three DC components is zero, both initially and thereafter, since the time constant is the same for all. The residual flux also tends to increase the fault current amplitude, but it is customary to exclude DC offset from the decrement curve. This exclusion of DC offset is necessary to ensure reliable overcurrent relay operation.

3.3 Fault Decrement Curves in Relaying Application

Many small generators were connected to electric utility distribution circuits in recent years and these small generators are normally protected by overcurrent relays. Even at large generating stations there are plenty of overcurrent protective devices such as overcurrent relays and fuses. Adequate operation of all these devices heavily relies on the high fault current availability. As shown above, high fault currents exponentially decay based on generator parameters such as E, Xd, Xd', Xd", Td', Td", and Ta. Therefore, the high fault currents may not be available only a second after the fault inception and an overcurrent relay with an operating characteristic curve above the decrement curve on the time-current coordination (TCC) sheet may not operate at all (as illustrated in Figure 2 – Generator Decrement Curve). **For adequate coordination and reliable relay operation, the overcurrent relay curve must be slightly below the decrement curve (without DC offset and also without automatic voltage regulation in service) as shown in Figure 10 – Coordination with Decrement Curve.**

As explained before, fault decrement curves can be easily constructed based on generator parameters such as E, Xd, Xd', Xd", Td', Td", and Ta. However, the best way is to get the decrement curves (Without DC offset and also without automatic voltage regulation in service. The automatic voltage regulation tends to increase the fault current amplitude and also tends to slow the exponential decaying. The DC offset also tends to increase the fault current amplitude.) directly from generator manufacturers.

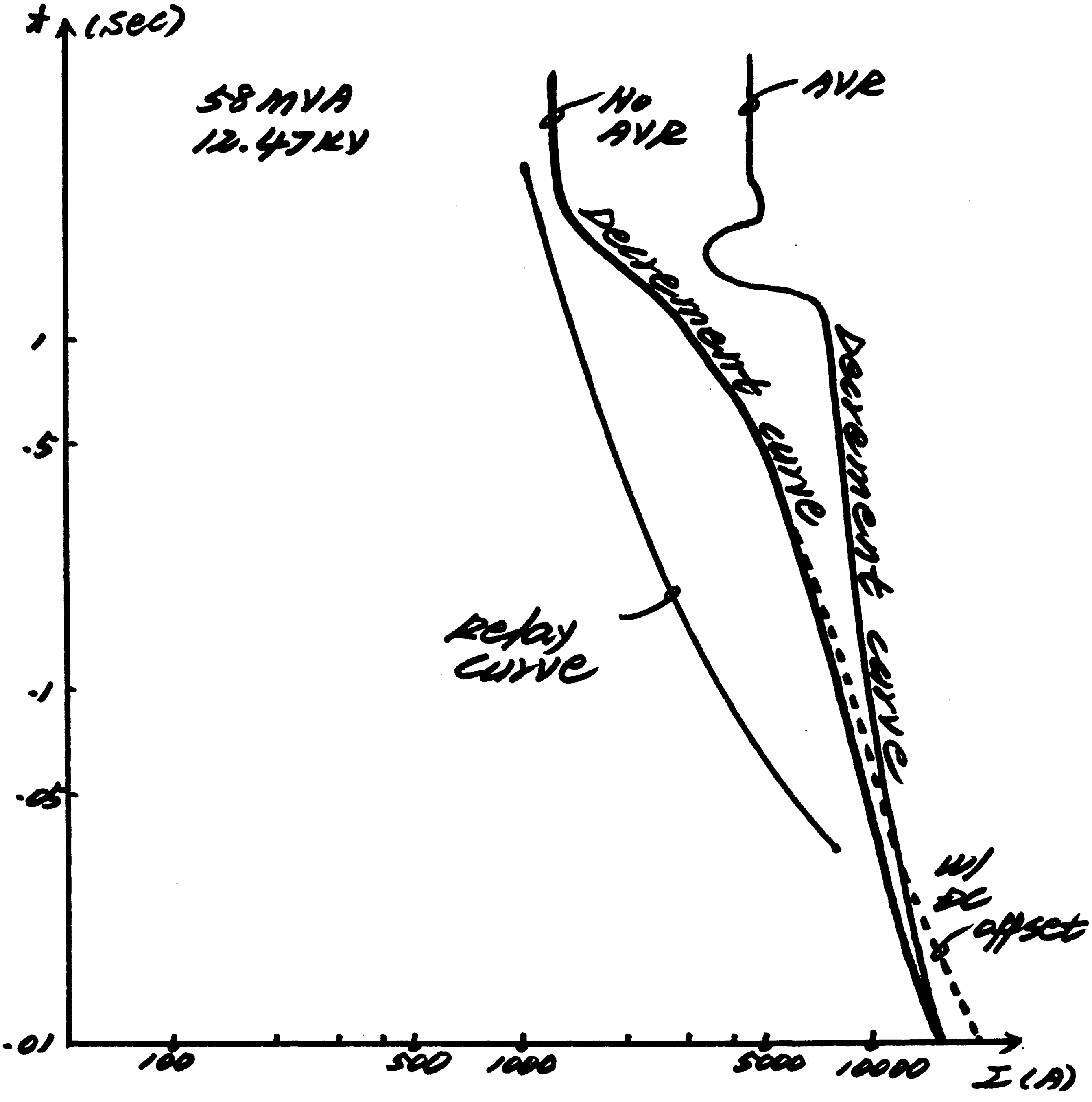

Fig. 10. Coordination with Decrement Curve

4. Conclusion

A primary objective of this paper was revisiting the old exponentially rising DC circuit transient theory and also the old exponentially decaying AC generator fault current theory (generator fault current decrement curve) because this transitional nature of DC & AC currents creates unique challenges to system protection & control engineers. It is my sincere hope that these two concepts will be properly applied to our daily chores such as control circuit design and relay setting calculation.