Reverse Power Flow during the Normal Startup and Improved Reverse Power Relaying Based on I^2t=3K

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I. Introduction

Due to seemingly sluggish operation of the existing integrated generation control systems at one of Chelan County PUD hydro power plants, the reverse power relaying (with 2% pick up level and 50-second time delay) tripped generator circuit breakers once in a while before hydro-generators were fully loaded to desired MW values. For example, two medium-size hydro-generators were tripped off due to reverse power relaying operation during the normal (automated) startup on the coldest day in January 2004 and consequently the desperately needed power production could not be accomplished.

A quick fix to nuisance trip problems was to increase the time-delay setting to 100 seconds, based on available MW recordings during the normal startup. As shown in Figure 1, Reverse Power Flow during the Normal Startup, the reverse power flow during the normal startup is real even though it may happen once in a while. Figure 2, Unsuccessful Startup due to Reverse Power Flow (Case 1), illustrates that a considerable amount, reaching 24%, of reverse power flow lasted at least 80 seconds and so a nuisance trip operation during the normal startup occurred due to sensitive reverse power relay settings.

The 100-second time delay setting seemed to be extremely long and the 2% pick up level seemed to be too low, so the author reviewed some of available reverse-power relaying schemes and reached the following conclusion:

1. The allowable reverse-power flow and acceptable duration for it are neither readily available nor easily deterministic.
2. The sluggish but normal governor operation is not adequately accommodated in setting calculation.
3. Generally, no coordination between all motoring protection schemes is attempted, so the unprotected motoring zone may not be obvious to application engineers.
4. No extensive test data useful in setting calculation is available.
5. The traditional reverse power relaying is primarily for mechanical damage protection against motoring. However, based on some of available data and test results, electrical damages seem to occur long before any serious mechanical damages.

6. The traditional reverse power relaying utilizes a fixed time delay characteristic, but a variable inverse-type characteristic is strongly desired.
7. A better reverse power relaying for electrical damage protection against motoring is needed and it can be developed.

This technical paper is intended as a summary of the author's current ***efforts to avoid all nuisance reverse power trips during the normal startup and to optimize relay settings without sacrificing any reverse power protection***. Setting philosophies presented in this paper are applicable primarily to salient-pole hydro-generators even though they may be applicable to solid-rotor turbo-generators with some minor modifications.

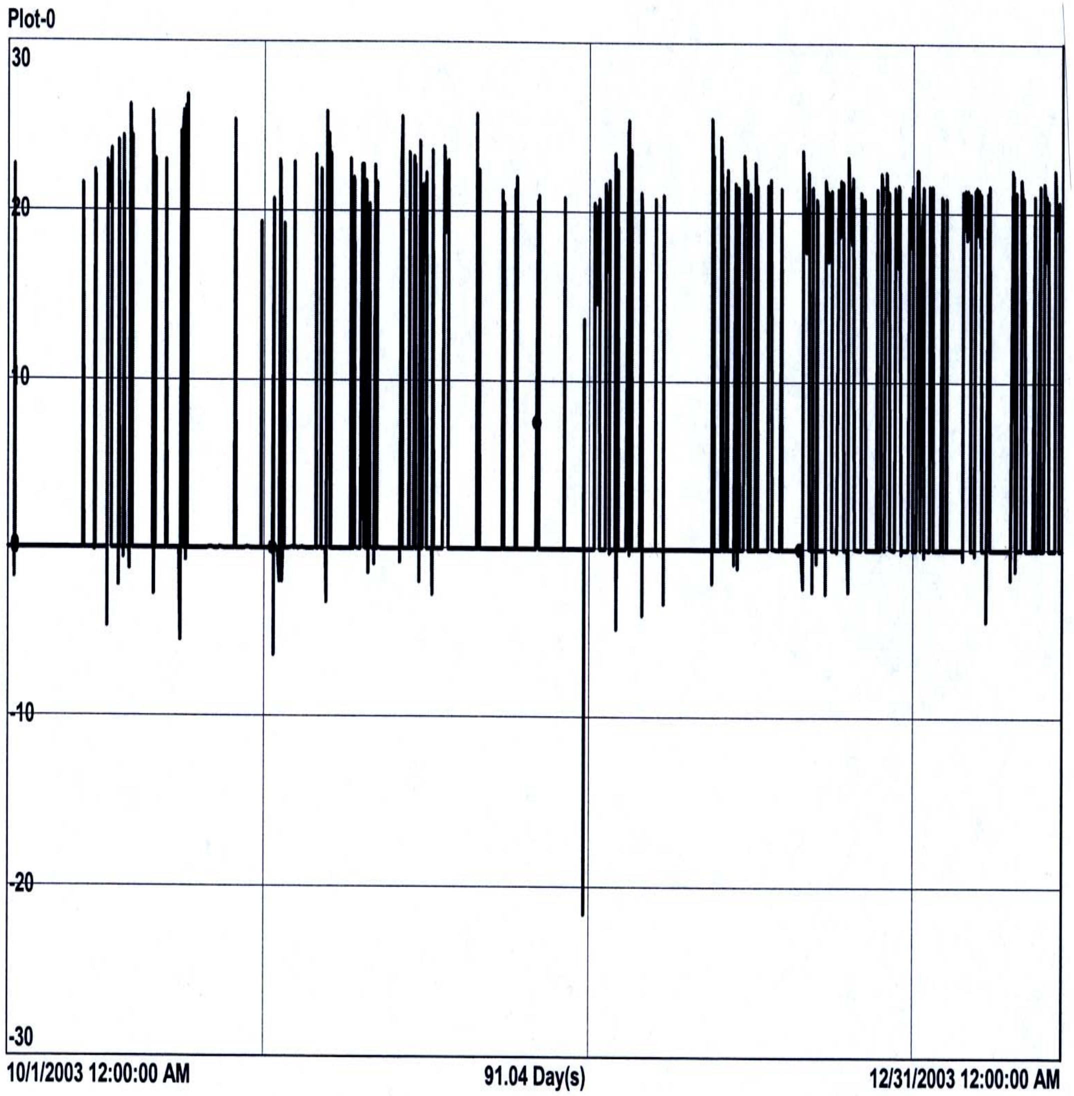

Figure 1. Reverse Power Flow during the Normal Startup

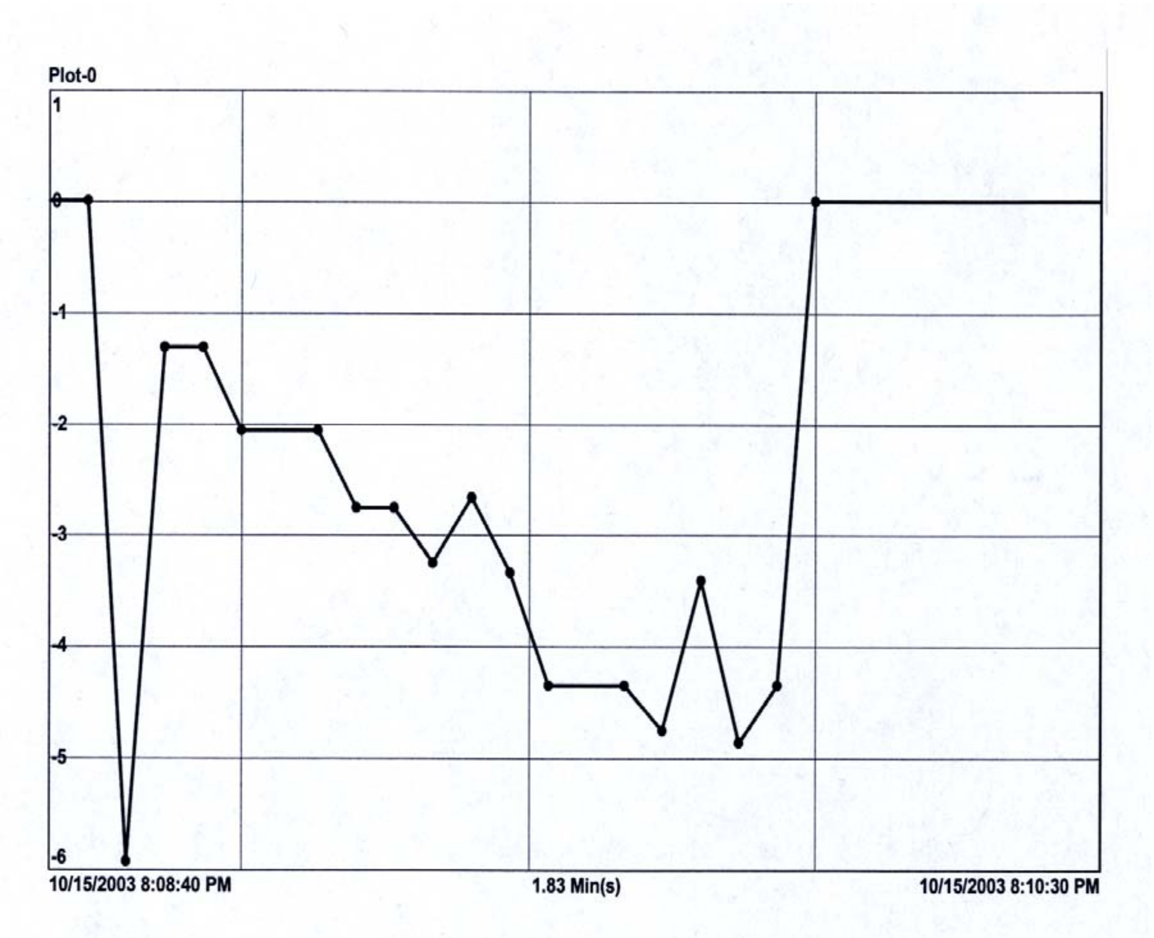

Figure 2. Unsuccessful Startup due to Reverse Power Flow (Case 1)

II. Fundamentals of Traditional Reverse Power Relaying

2.1 Hydro-generator Motoring Protection

- **Traditional Hydro-generator Motoring Protection**: Potentially, motoring may result in immediate damages to the generator rotor, so no prolonged motoring operation should be allowed even though lightly-loaded synchronous motoring may not be harmful. Normally, all motoring hydro-generators should be tripped off immediately and so all harmful motoring should be detected by loss-of-field relaying, out-of-step relaying, and/or reverse power relaying in a timely manner.

  Typically, 30-second time delay and 2% pick up settings for reverse power relaying are recommended by relay manufacturers. It appears that the 30-second time delay might have been originated from the permissible I_2 limit $\{(I_2)^2t=10$ at $0.6\ I_2\}$, which is too conservative and impractical for hydro-generators with $(I_2)^2t=40$. On the other hand, it is also true that a severe case of induction motoring may destroy the generator in 3 seconds as indicated in one of IEEE

Tutorials[2]. Clearly, we can see that the traditional one-step reverse power relaying with 30-second time delay and 2% pick up settings will not protect hydro-generators against any severe case of induction motoring at all.

In addition, only a handful of research papers appear to have been written recently and they did not seem to present any field data useful in relay setting calculation, not to mention that those settings recommended by relay manufacturers frequently caused nuisance trips during the normal startup.

- **Historical Information regarding Damages due to Motoring**: Based on some available information, at least one generator manufacturer actually conducted a series of tests so as to understand damages due to motoring and concluded that the generator rotor damages caused by motoring are very similar to those caused by I_2 in the stator winding.

  In addition, one of IEEE Tutorials[2] suggests that the reverse power protection may be based on $I_2^2t=K$ and this concept has been successfully used by many relay application engineers. However, it appears that no technical papers truly relate $I_2^2t=K$ to the traditional power-based reverse power relaying other than stating, "The time after which rotor damage will generally occur can be approximated by using the equation for the short time negative-sequence capability of the generator $I_2^2t=K$." K is a constant depending on generator design and size, and I_2 is a permissible negative-sequence current. For example, K is 40 for salient-pole hydro-generators and I_2 is 10 for salient-pole hydro-generators with connected amortisseur windings.

2.2 Hydro-generator Motoring Types

- **Types of Hydro-generator Motoring**: Depending on the conditions of head gate opening, tail gate or draft tube gate opening, blade tilt, wicket gate opening, rotor speed (locked-rotor, subsynchronous, near-synchronous, or synchronous), field excitation, and water in the draft tube (unwatered or watered), the hydro-generator motoring can range any motoring from the most severe locked-rotor induction motoring to the perfectly harmless lightly-loaded synchronous motoring. For clarity and simplicity of this technical paper, the author assumes that the hydro-generator motoring consists of locked-rotor induction motoring, subsynchronous induction motoring, near-synchronous motoring, and synchronous motoring. The locked-rotor induction motoring is normally termed as accidental energization or inadvertent energization in other papers.

  The near-synchronous ***motoring is not uncommon during the normal startup of hydro-generators*** because the generator breaker is normally closed in the "Slow" synchroscope zone. However, the near-synchronous motoring is not common at all during the manual startup of hydro-generators because hydro operators close the generator breaker normally in the "Fast" synchroscope zone. Also, based on our past experience, synchronous motoring (actually, subsynchronous induction motoring) happened occasionally due to governor control system malfunction, draft tube gate control system malfunction, or generator breaker failure. However, our hydro power plants have never experienced any locked-rotor induction motoring probably because of our strict safety rules and regulations.

The near-synchronous ***motoring is also somewhat common during the normal shutdown of hydro-generators*** due to sluggish operation of governor control systems, as mentioned earlier.

Generally, the hydro-generator startup operation involves a series of control circuits such as governor control, excitation control, automatic synchronizer, startup control, and generator breaker control. Any imperfection of these control schemes, in addition to inherently imperfect hydraulic operation of blade tilt and wicket gates, may cause the undesirable reverse power flow.

III. Motoring Power Data

3.1 Motoring Power Data Published by Relay Manufacturers

- **Motoring Power Requirements Published by General Electric and Westinghouse**: Per one of GE Instruction Books on the Generator Protection, "The motoring power requirements in % of unit rating for hydraulic turbines are 2% - 100%. Larger powers are normally taken by turbines having submerged impellers and lower powers may be taken by turbines in the unwatered draft tube."

  Per Westinghouse Applied Protective Relaying, "When the blades are under the tail-race water level, the percent of kW rating required for motoring is high – probably well over 2.0%. From 0.2 to 2.0% kW is required for the turbine to motor when the blades are above the tail-race level. For turbines using a Kaplan adjustable-blade propeller, the flat blade condition probably requires less than 0.2% kW to motor."

  Clearly, their recommendations are not really specific and too general to be used for actual relay setting calculation. It appears in the author's mind that the reverse-power relaying lacks reliable field data for relay setting calculation.

3.2 Motoring Power Data Recorded in the Field

- **Review of Hydro-generator Motoring Power Magnitudes and Durations**: Some figures are shown in Westinghouse Applied Protective Relaying and one of GE Instruction Books on the Generator Protection, but no specific details are given as indicated above. Generally, the magnitudes and durations depend on a number of parameters such as machine design, machine operation, governor control system, excitation system, automatic synchronizer, sync check relay settings, and operating conditions. Fortunately, our hydro power plants track some motoring data during the normal startup (basically, near-synchronous motoring) as shown below and so more realistic reverse power relay settings can be made to allow the sluggish but realistic governor operation without exceeding any critical withstand limits.

Generator	**Rating in MW**	**Reverse Power in MW during the Normal Startup**
B1	23	3.2, 4.2, 3.4
B2	23	1.5
B3	16.7	5, 2.4, 3.7
B5	25	5.5
B7	25	5.9,5.2

As shown above, the motoring power requirements are relatively high and so we can see why manufacturers' recommended settings will not work very well. The near-synchronous motoring problems during the normal startup existed over the past 14 years or longer at our hydro power plants, but have not yet damaged any generator rotors.

Generally, the generator rotor is slightly lagging but accelerating at the moment of generator breaker closing and so the generator will take power from the system until corrected by the governor control system. This near-synchronous motoring is normally corrected within 5 – 20 seconds, but it may take 60 seconds sometimes. For example, B1 took 55 seconds to start loading in June 2003. Therefore, the time delay of 30 seconds may interfere with the normal governor control operation and cause nuisance reverse power trips**.** Based on our past experience, even the 50-second time delay was not sufficient enough to allow occasional sluggish governor control operation.

Based on our recorded data, it appears that the near-synchronous motoring occurs frequently (approximately every 5 starts) at two of our hydro power plants, but it occurs very infrequently (approximately once a month) at our other hydro power plants.

The near-synchronous motoring rarely occurs during the automated shutdown, but it happens once in a while. For example, B5 took 22MW for approximately 10 seconds in Nov 2003, and also took 4 MW for approximately 20 seconds in the same month.

Generator	**Rating in MW**	**Reverse Power in MW during the Normal Startup**
U1	54	1.42
U4	54	2.3
U8	54	2.8
C10	132	4.7, 5.2
C11	132	5.7, 7.2, 5.9

Some (20+) years ago at one of our hydro power plants, one of eleven generators was forced to motor for a while due to generator breaker failure. At that time during the normal shutdown the wicket gates were successfully closed, the field breaker was successfully opened, but the generator breaker failed to open. Apparently, the subsynchronous induction motoring for at least 10 minutes severely damaged rotor pole pieces and so all rotor pole pieces had to be replaced. However, no major damage was done to the stator winding, and no mechanical damage to turbine and shaft was observed at all.

- **Review of Reactive Power Magnitudes and Durations during the Normal Startup**: Based on the field data from 30 hydro generators at 3 hydro power plants during the normal startup, it appears that the reactive power magnitudes are insignificant as long as the automatic synchronizers with voltage matcher function properly.

- **Factors Affecting Motoring Power Requirements**: Hydro-generators are quite complex rotating machines, so it may be foolish to attempt to accurately estimate motoring power requirements during the normal startup. However, relay application engineers need some rules-of-thumb and so the following is presented for general information only:

  - **Inertia Constant (H)**: Inertia constants are 1.93 for B1 & B2, 2.66 for B3, 1.99 for B5 & B7, 0.75 for U1 - U8, and 2.89 for C10 & C11. U units with the smallest inertia constant seem to require a very small amount of motoring power as expected.
  - **Discharge Ring Diameter vs. Rotor Diameter**: The discharge ring diameter is larger than the rotor diameter for all horizontal-shaft U units, but the opposite is true for all other vertical-shaft units. Interestingly, regardless of machine sizes, all vertical-shaft units seem to have the approximately same motoring power magnitudes.

- **Machine Size**: B3 is the smallest unit with a relatively large inertia constant. Interestingly, B3 has the largest motoring power during the startup.
- **Governor Control Type**
- **Droop Setting**: The droop setting is 5% corresponding to 3 cycles in accordance with WECC requirements.

Figures 3 through 6 illustrate the reverse power flow during the startup and shutdown, as described above.

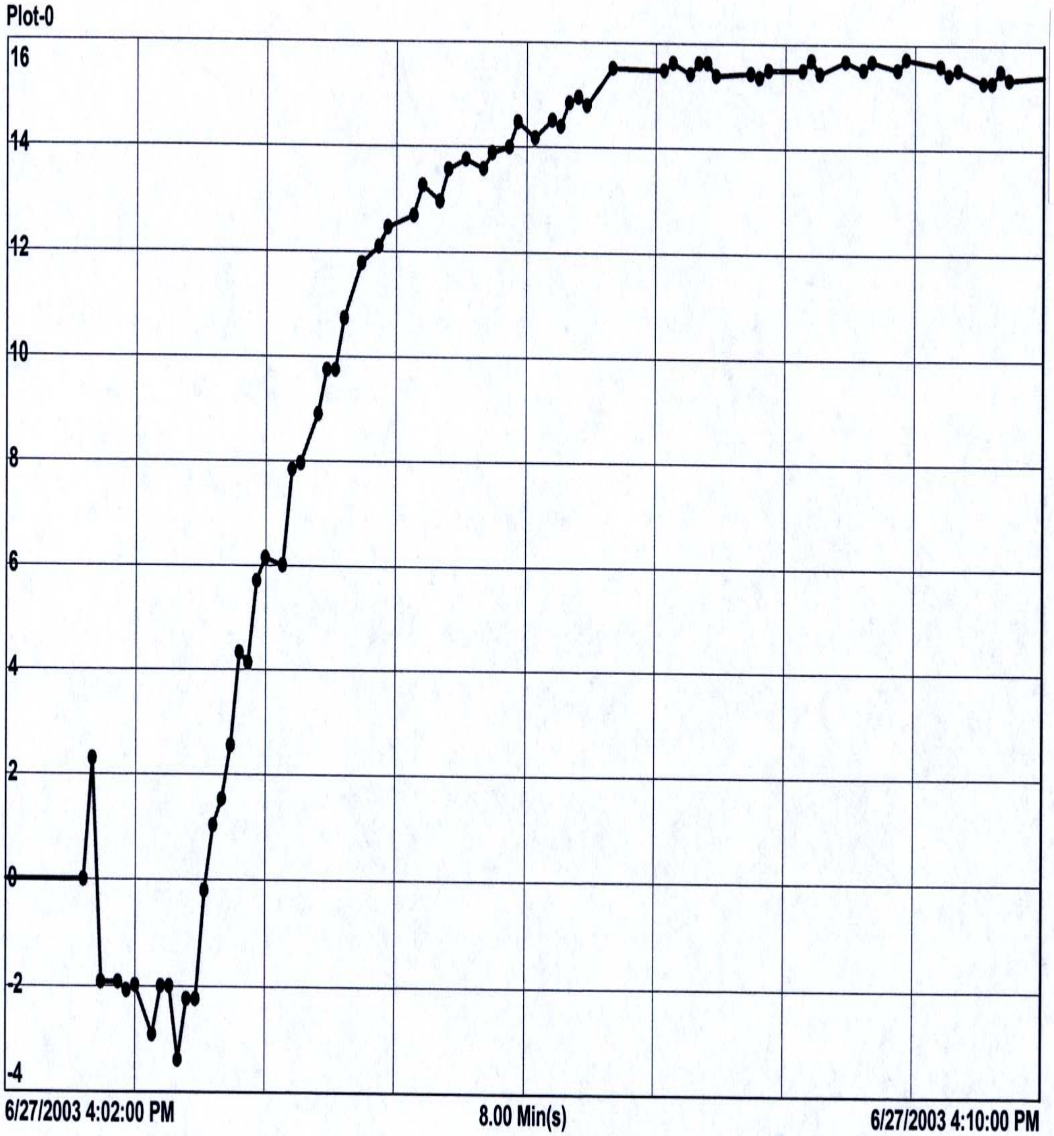

Figure 3. Successful Startup after Reverse Power Flow

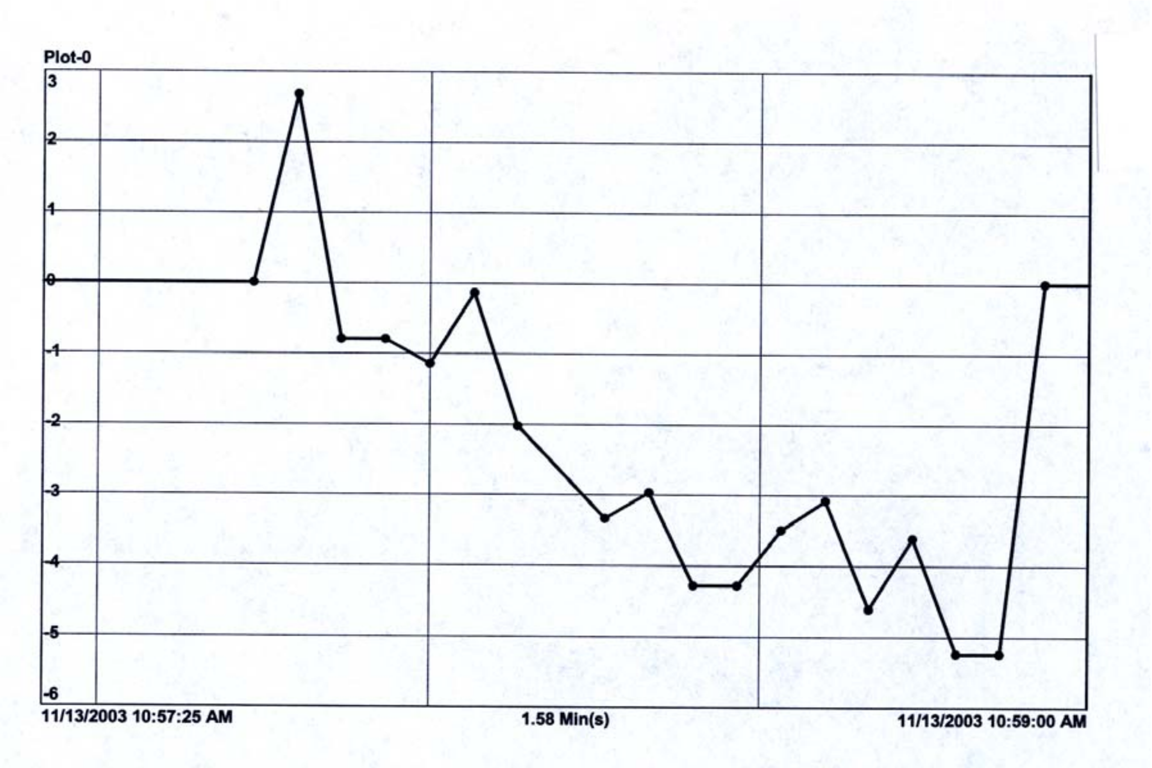

Figure 4. Unsuccessful Startup due to Reverse Power Flow (Case 2)

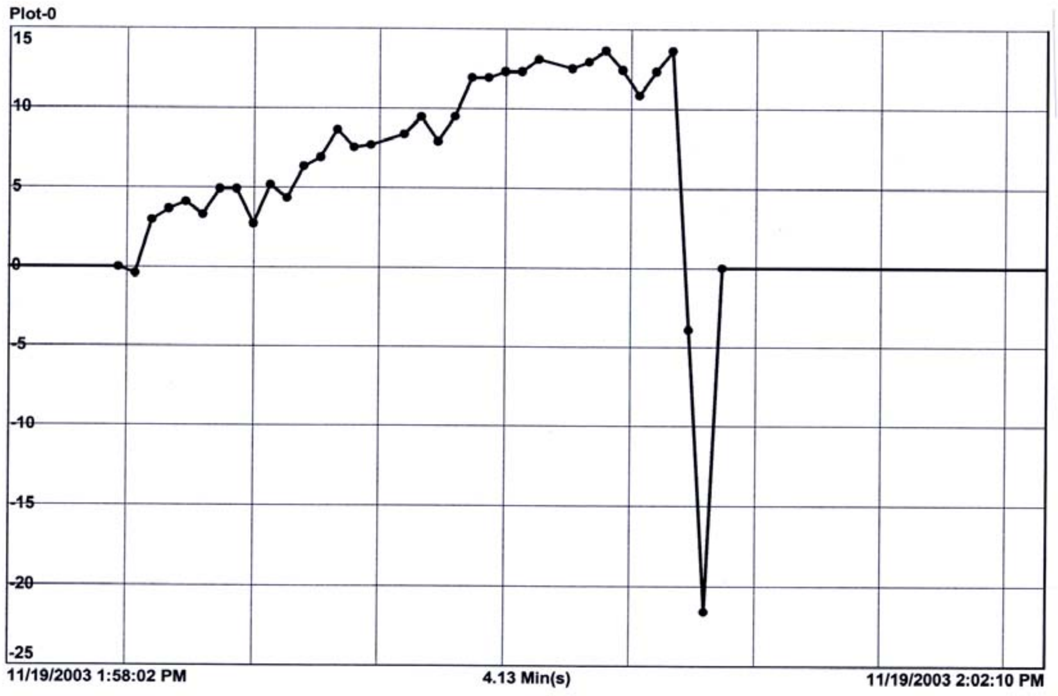

Figure 5. Reverse Power Flow during the Abnormal Shutdown

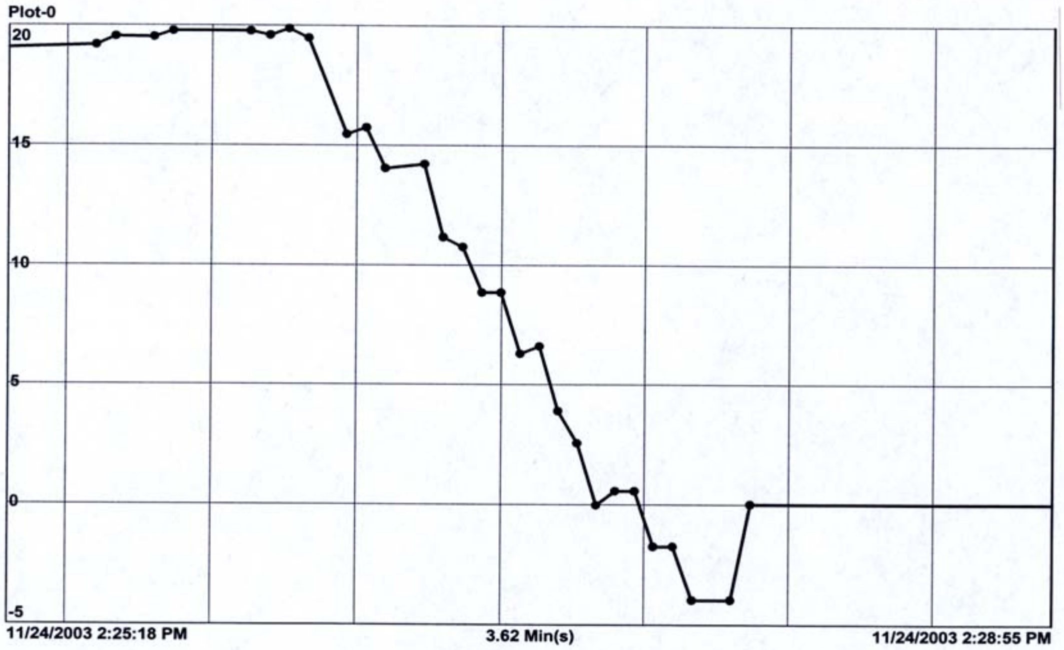

Figure 6. Reverse Power Flow during the Normal Shutdown

IV. Hydro-generator Motoring Withstand Capability

4.1 Hydro-generator Capability Curve

- **Review of Hydro-generator Capability Curves**: Even though many technical references and textbooks illustrate how to construct generator capability curves, the author strongly recommends that generator capability curves prepared by generator manufacturers should be used for all engineering purposes. Figure 7, Generator Capability Curve on P-Q Plane, illustrates a sample hydro-generator capability curve shape and Figure 8, Generator Capability Curve on R-X Plane, illustrates the exactly same generator capability but on the R-X plane. For application engineers interested in constructing generator capability curves, they can be easily constructed, provided that certain key parameters (rated voltage, synchronous reactance, dc circuit impedance, thermal limit of stator winding, thermal limit of rotor winding, thermal limit of stator core ends, thermal limit of rotor core surface, prime mover capability, steady-state stability limit, maximum field current, center for field current circles, and constant field current circles) are readily available, as illustrated in many references and textbooks.

- **Mechanical Strength or Capability of Hydro-generators**: In general, the mechanical capabilities against motoring are not readily available. However, based on the author's research and past experience, the following is presented for general information only:

- Per ANSI/IEEE C37.102, IEEE Guide for AC Generator Protection, "Due to saliency, the normal hydro-generator may carry 20 to 25% of normal load without field and not lose synchronism."
- Per ANSI/IEEE C37.102, IEEE Guide for AC Generator Protection, "Motoring of a generator occurs when for some reason the energy supply to the prime mover is cut off while the generator is still on line. When this occurs, the generator will act as a synchronous motor and drive the prime mover. While this condition is defined as generator motoring, the primary concern is the protection of the prime mover which can be damaged during a motoring condition."
- Per IEEE Standard 492, IEEE Guide for Operation and Maintenance of Hydro-generators, "Operation of a generator out-of-synchronism, with part or full-field excitation maintained, places the most severe type of duty on the unit. Such operation produces heavy surge currents in the stator windings whose magnitude may exceed those associated with the machine short-circuit requirements of ANSI C50.12 and cause serious damage to the winding. Such operation also produces torque reversals which create in many parts of the unit high mechanical stresses of magnitudes that may be several times those produced by rated torque."
- Based on the author's conversation with a hydro-generator manufacturer's designer, his series of motoring tests indicated that generator rotor damages due to motoring were very similar to those caused by I_2 in the stator winding but no mechanical damage was observed.
- Based on the author's research and conversation with hydro operators and mechanics, a serious motoring incident and occasional not-so-serious motoring incidents caused no apparent mechanical damages.
- In general, sudden accelerating/decelerating torques applied to the generator turbine and shaft/rotor result in a form of vibration, growling, humming, or screeching, as normally sensed by hydro operators during the hydro-generator operating cycle. Technically, motoring can be viewed as sudden application of accelerating/decelerating toques (hydrodynamic or electromagnetic forces) to the generator turbine and shaft/rotor, and it occurs very often (e.g., during the startup prior to synchronization, during the synchronization, during the shutdown after wicket gates are closed, ramping down, ramping up, inadvertent energization or locked-rotor induction motoring, governor control failure, sudden loss of field, short circuit faults, breaker failure, sudden system configuration changes, out-of-step, power swing, full load rejection, etc.). However, no serious mechanical damages have been observed yet at our hydro power plants.

Based on all information gathered, ***electrical damages seem to occur long before any serious mechanical damages***, even though our primary concern is the protection of prime mover which can be damaged during the severe motoring conditions. Clearly, ***it appears that the mechanical strength of hydro-generators is superior to electrical strength***.

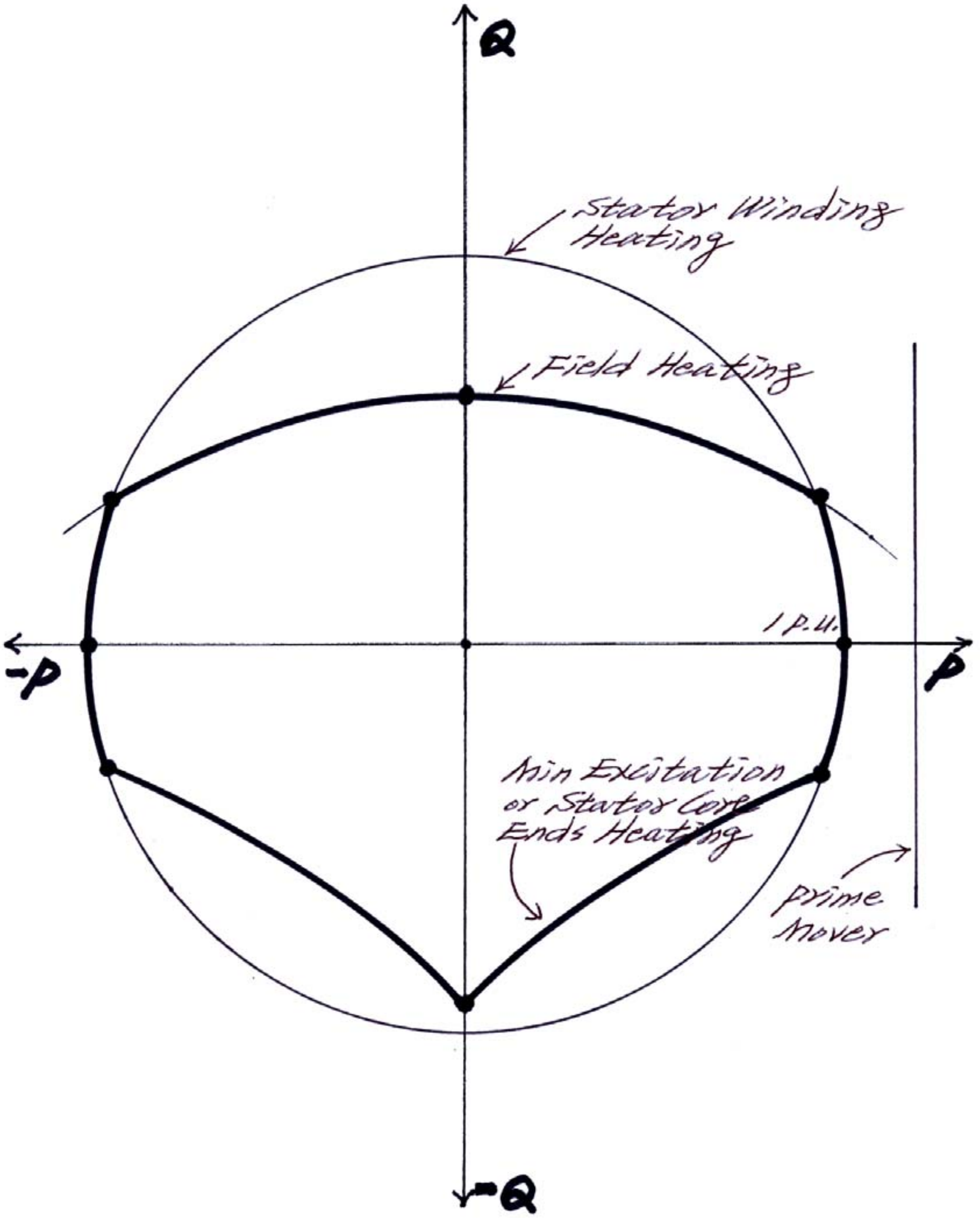

Figure 7. Generator Capability Curve on P-Q Plane

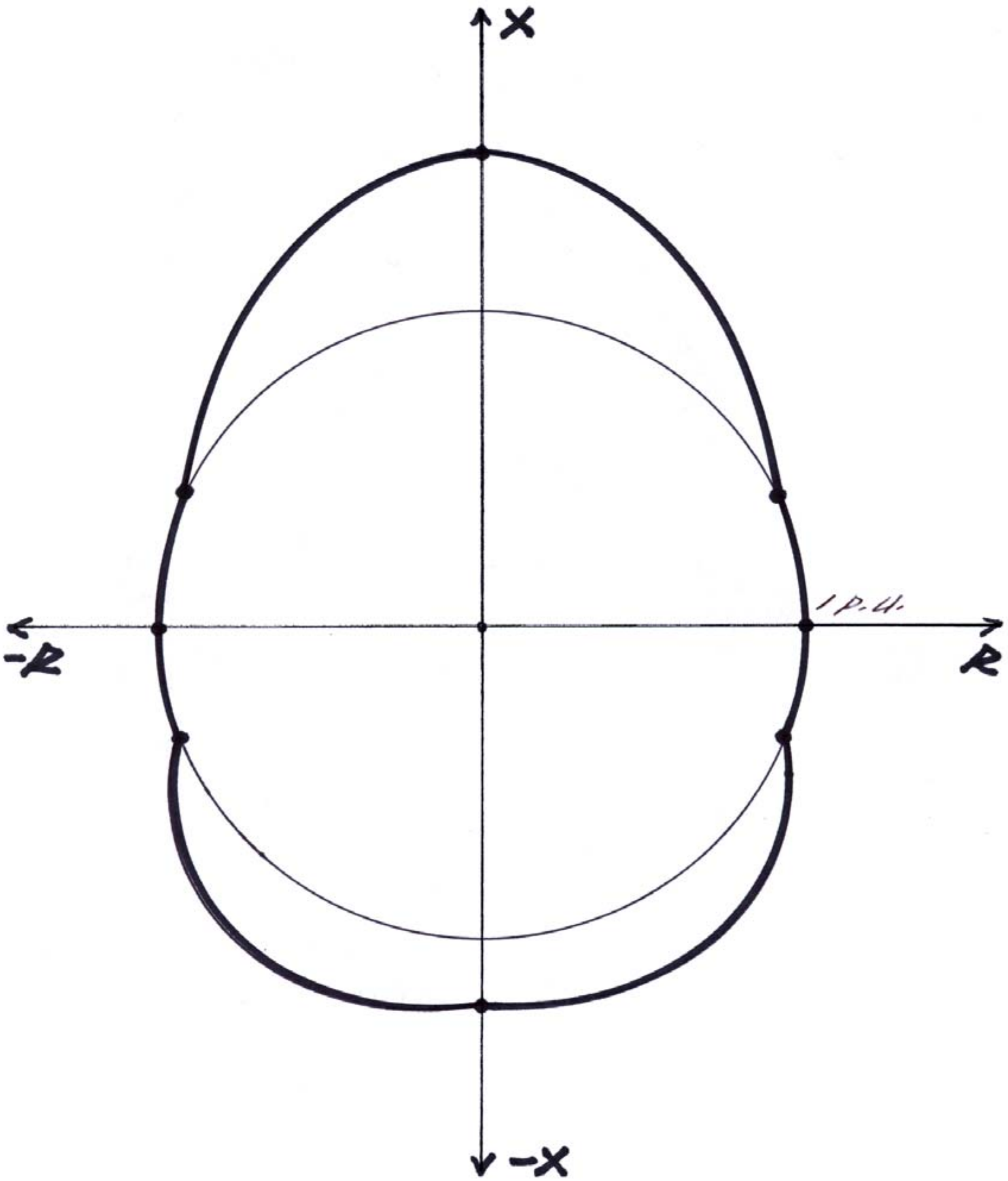

Figure 8. Generator Capability Curve on R-X Plane

4.2 Hydro-generator Motoring Withstand Capabilities for Synchronous Motoring and Induction Motoring

- **Synchronous Motoring Withstand Capability**: In general, lightly-loaded synchronous motoring is not harmful at all, as indicated previously. In addition, the hydro-generator's synchronous motoring withstand capability appears to be much higher than its induction motoring withstand capability.

- **Induction Motoring Withstand Capability**: Some generator relaying professionals suggest that the reverse power protection may be based on $I_2^2t=K$ of the generator. K is typically 40 for hydro-generators and I_2 is 10 for hydro-generators with connected amortisseur windings. For unbalanced faults, the generator rotor is subjected to I_2-caused 120-cycle currents. For motoring, the generator rotor is subjected to 0.01 – 60-cycle (slip frequency) currents caused by I in the stator winding. Theoretically, the generator rotor is subjected to 60-cycle currents during the locked-rotor induction motoring and subjected to less than 1-cycle currents during the near-synchronous motoring.

  Regardless of actual causes, I_2 or I in the stator winding, the initial effect of ac currents in the rotor core is rapid heating in iron paths near the rotor surface. These paths primarily consist of wedges, rotor iron, and retaining rings. The depth of current penetration is a fraction of an inch, considerably less than the depth of the rotor windings. The contacts between these components are points where a localized, rapid temperature rise occurs, due mainly to arcing. Damage to rotor windings, if it occurs, would result from the loss of wedge support, rather than heating. Because of the low depth of current penetration, the rotor windings would not likely experience an excessive temperature rise and, therefore, would not be thermally damaged[2].

  Based on our engineering principles in electromagnetic energy conversion, it is known that the eddy-current loss is proportional to the square of frequency, the hysteresis loss is directly proportional to frequency, and the eddy-current loss is normally higher than the hysteresis loss. In other words, the 120-cycle eddy-current loss is four times the 60-cycle eddy-current loss and the 120-cycle hysteresis loss is twice the 60-cycle hysteresis loss. In addition as described in Electromagnetic & Electromechanical Machines authored by Leander Matsch, the flux in transformers, reactors, and ac electromagnets oscillates along a path that is practically fixed while the rotors of rotary electromagnetic devices such as motors and generators are subjected to fluxes that change their direction by virtue of rotation. The rotational hysteresis loss is greater at low magnetization than the corresponding oscillating hysteresis loss, while at high flux densities the rotating hysteresis loss decreases becoming quite low at very high flux densities. Therefore, the ***reverse power protection based on $I^2t=3K$ is more appropriate for all harmful induction motoring, dealing with slip frequency currents on the rotor surface***, and very conservative for synchronous/near-synchronous motoring**.**

  For K=10 (typical to directly cooled turbo-generators) and I=4 p.u. during the locked-rotor induction motoring, the generator rotor will be severely damaged in less than 2 seconds based on $I^2t=3K$. For K=40 (typical to hydro-generators) and I=4 p.u. during the same locked-rotor induction motoring, the generator rotor will be damaged in 7.5 seconds. This failure timing agrees to the previously-mentioned statement, “A severe case of induction motoring may destroy the generator in 3 seconds.”

4.3 Hydro-generator Thermal Withstand Capability Specifications

- **Hydro-generator Withstand Capabilities**: Generally, hydro-generators are required to meet the following:

  - **Short Circuit Withstand Capability**: The generator shall be capable of withstanding, without harmful deformation or damage, a 3-phase short circuit, or any other short circuits, at its terminals for 30 seconds when operating at rated MVA, power factor, and 105% of rated stator voltage, with fixed excitation level, in accordance with ANSI C50.12.
  - **Overload Withstand Capability of Stator Winding**: The generator shall be capable of withstanding 150% of rated stator current for two (2) minutes, without harmful deformation, mechanical damage, or other damage, near rated voltage, without exceeding rated temperature rise.
  - **Overload Withstand Capability of Field Winding**: The field windings shall be designed to safely withstand two (2) times rated field current for not less than one (1) minute.
  - **Unbalanced Operation Withstand Capability (Critical to Rotor Temperature Rise)**: The generator shall be capable of withstanding, without damage, the effects of a continuous current imbalance corresponding to a negative-phase sequence current of 10% of rated stator current provided that the rated output is not exceeded and the maximum current does not exceed 105% of rated current in any phase at rated power factor and voltage. The specified temperature rise shall not be exceeded during this unbalanced operation.
  - **$(I_2)^2t=K$ (Critical to Rotor Temperature Rise)**: Under fault conditions, the generator shall be capable of withstanding, without damage, per-unit negative-sequence current (I_2), expressed in terms of rated stator current and duration of fault in seconds (t), up to values which give an integrated product $(I_2)^2t$ not less than or equal to 40.

For a phase-to-phase fault at the generator terminal which will generate the largest negative-sequence current, the fault current or stator winding current (I) is equal to 1.732 times the negative-sequence current (I_2). ***The relationship $I=1.732I_2$ also implies that a motoring current amounting to 17.32% of permissible I_2 is permissible***. Based on the last requirements, $(I / 1.732)^2t$ should be equal to K, which yields $(I)^2t=3K$. This result is exactly the same as the previously-derived equation based on the eddy and hysteresis losses of the rotor iron core. One caution with this equation $(I)^2t=3K$ is that it should not be used for continuous operation capability at all because I represents the stator winding current containing 58% I_2.

For a 3-phase fault at the generator terminal, the average stator winding current (I) may be approximately 2 p.u. for the first 30 seconds and so $(2)^2$ times 30 is equal to 120. Again, $(I)^2t=3K$ can be derived from the first requirements provided that t is less than or equal to 30 seconds.

- **Permissible I**: For all hydro-generators at our generating plants, all generator rotors have non-connected damper windings but those damper windings are actually connected through other iron paths. Practically, all of our generator rotors are considered to have the connected damper windings in determining the generator negative-sequence current withstand capability. For hydro-generators with the connected damper windings based on ANSI C50.13, the permissible I_2 is 10% and so the permissible I is 17.32%. This permissible I of 17.32% actually explains why our hydro-generators have not yet had any damage to rotor poles all these years even though the reverse power flow during the normal startup has occurred frequently.

  In addition, the permissible I largely depends on effectiveness of the generator cooling system, so a hydro-generator with a very effective cooling system should be able to handle more than the permissible I_2 shown in ANSI C50.13.

As a conclusion, ***$I^2t=3K$ and $I=1.732I_2$ adequately represent hydro-generator mechanical/electrical/thermal withstand capabilities for 3-phase faults, phase-to-phase faults, synchronous motoring, and induction motoring***.

V. Improved Reverse Power Relaying Schemes Based on $I^2t=3K$ & $I=1.732I_2$

5.1 Protection Schemes Which May Detect Motoring

- **Underfrequency Relaying to Detect Motoring**: Since the generator protection relay sees the system frequency, it is not effective and in fact it cannot detect motoring at all. In addition, at least one manufacturer’s relays may not operate properly outside the operating frequency range of 20 – 70 cycles.

- **Negative-sequence Overcurrent Relaying to Detect Motoring**: Not effective at all. In fact, it cannot detect motoring at all because 3-phase motoring currents are balanced.

- **Voltage-controlled Overcurrent Relaying to Detect Motoring**: It may detect motoring during the loss-of-field-caused motoring. Overall, it may provide limited motoring protection but is not really effective.

- **Out-of-Step Relaying to Detect Motoring**: It is very effective during the unstable power swing-caused motoring even though ineffective for other types of motoring. As stated in IEEE Standard 492, IEEE Guide for Operation and Maintenance of Hydro-generators, “Operation of a generator out-of-step, with part of full-field excitation maintained, places the most severe type of duty on the unit. Such operation produces heavy surge currents in the stator windings whose magnitude may exceed those associated with the machine short circuit requirements of ANSI C50.12 and cause serious damage to the winding. Such operation also produces torque reversals which create in many parts of the unit high mechanical stresses of magnitudes that may be several times those produced by rated torque. Normally, no intentional trip time delay is recommended for this type of relaying."

Generally, the power swing frequency ranges 0.1 to 5 Hz and the power system stabilizer, used with high initial response ratio excitation systems requiring the voltage response time of 0.1 seconds or less, is needed to neutralize the negative damping action of voltage regulators.

- **Loss-of-Field Relaying to Detect Motoring**: It is very effective during the loss-of-field-caused motoring or locked-rotor induction motoring, but may not be effective for synchronous motoring and near-synchronous motoring.

  As stated in one of IEEE Tutorials[2], "when the generator loses its field, it tends to overspeed and so operates as an induction generator causing rotor temperatures to increase due to slip-induced eddy currents in the field winding, rotor body, wedges and retaining rings. The high reactive current drawn by the generator from the system can overload the stator winding causing the stator temperature to increase. The machine damage time due to the above causes can be as short as 10 seconds to several minutes. The time to damage depends on type of machine, type of excitation loss, governor characteristics, and load on the generator. A typical loss-of-field time delay setting is 0.5 seconds."

5.2 Directional Phase Overcurrent Relaying (Preferred)

- **Need for Sensitive Directional Phase Overcurrent Relaying to Effectively Detect All Harmful Motoring**: Clearly, ***the generator rotor damages due to motoring are thermal in nature and so the reverse-power relaying based on*** $I^2t=3K$ ***and*** $I=1.732I_2$ ***makes more sense***. Even though it makes sense to monitor the reverse power flow for mechanical damage protection, ***it actually makes more sense to monitor the reverse current flow for electrical damage protection***. The traditional reverse power relaying will protect generators against motoring only in case of motoring at relatively high power factors. Ideally, the reverse power relaying should utilize the time overcurrent characteristic (termed as "variable inverse-type characteristic" in this paper) such as directional phase overcurrent relaying, but all commercially available reverse power relays use the definite time-delayed trip scheme only. Only the sensitive directional phase overcurrent relaying will adequately relate $I^2t=3K$ and $I=1.732I_2$ to motoring in the author's mind. Since the sensitive directional phase overcurrent relaying (if used) tries to detect a small portion of the rated current and the current transformers are subjected to the rated current constantly, current transformers with a very high rating factor are highly desirable, as briefly stated in one of IEEE Tutorials on The Protection of Synchronous Generators[2].

There are many relaying schemes mentioned in details in IEEE Tutorial 95 TP 102 and ANSI/IEEE Standard C37.102. One of them is the directional phase overcurrent relaying mentioned as one of recommended inadvertent (or accidental) energization protection schemes for turbo-generators.

Overall, it appears that ***the sensitive directional phase overcurrent relaying scheme mimics the thermal damage characteristic during the hydro-generator motoring best and it can minimize the annoying nuisance trips most effectively without sacrificing any reverse-power protection***.

5.3 2-step Reverse Power Relaying (Semi-preferred)

- **Optimizing Traditional Reverse-Power Relay Settings**: Since it appears that each group of hydro-generators displays its own unique reverse power characteristics, it may be beneficial for each generator group to have its own unique settings even though the following proposed settings appear to be the same for all generators. Ideally, we should be using the directional phase overcurrent relaying (not available from our integrated generator protection relays), but at least should be using the 2-step reverse power protection as suggested below.

Generator	**Rating in MW**	**1st Step Settings**	**2nd Step Settings**
B1, B2, and B4	23	20% and 80 sec	50% and 4 sec
B3	16.7	20% and 80 sec	50% and 4 sec
B5, B6, and B7	25	20% and 80 sec	50% and 4 sec
B8, B9, and B10	25	20% and 80 sec	50% and 4 sec

The above settings may seem very high, but they still are somewhat conservative. Since the permissible I is 17.32% as derived previously and the reactive power flow during the normal startup is insignificant, I=20% is appropriate. With $I^2t=120$ for our hydro-generators, the permissible time for I=20% is 50 minutes, that for I=50% is 8 minutes or 480 seconds, and that for I=400% (locked-rotor induction motoring) is 7.5 seconds. With the above settings in place, it is anticipated that the loss-of-field relaying element and/or the out-of-step relaying element may operate prior to reverse power relay timed-out for certain harmful motoring operations.

One thing we have to understand is that the traditional reverse power relaying does not use the current magnitudes even though the locked-rotor induction motoring currents, highly reactive, may be 3 to 4 times the rated generator currents**.** For the hydro-generators above, the maximum calculated locked-rotor induction motoring currents are 3.7 p.u. for B1 & B2, 4.35 p.u. for B3, 3.7 p.u. for B4, 3.33 p.u. for B5 – B10. However, it is anticipated that these high currents should decrease to approximately 75% within a few cycles or 33 milliseconds.

One integrated generator protection relay type at our hydro power plants has 1 reverse-power trip, 1 reverse-power alarm, and 1 low forward power trip, so it can be programmed for 2-step reverse-power relaying by using the reverse-power trip as a first-step trip and the reverse-power alarm as a second-step trip.

Another integrated generator protection relay type at our hydro power plants has 1 reverse-power trip and 1 low forward power trip, so it can be programmed easily for the 2-step reverse-power relaying.

This 2-step reverse power relaying scheme is obviously better than the traditional 1-step scheme, but it may be used as a compromising reverse power relaying scheme only if the preferred directional phase overcurrent relaying is unavailable.

5.4 Coordination between Motoring Protection Schemes

- **Coordination between Loss-of-field Relaying, Out-of-step Relaying, and Reverse Power Relaying**: Even though all three types of relaying are used directly or indirectly to protect generators against the harmful motoring, it is not customary to plot all three characteristics on the same R-X plot and so no adequate coordination between them is normally attempted. However, plotting all three characteristics on the same R-X plot or P-Q plot appears to be the only fair way to understand the coordination between them.

  One important thing in plotting all three characteristics on the same R-X plot or P-Q plot is that there are two (2) dissimilar motoring requirements such as one for synchronous motoring and the other for induction motoring.

5.5 Concentric Circle Coordination Sheet Based on $I^2t=3K$ & $I=1.732I_2$

- **Concentric Circle Coordination Sheet** (called "**CCC Sheet**"): The Concentric Circle Coordination Sheet was primarily developed for the author's personal use so as to adequately coordinate between reverse power relaying, out-of-step relaying, and loss-of-field relaying. Since it is not a standard coordination tool commercially available to everybody, it is presented here for general information only. The following briefly explains how to use it and what some of application limitations are.

- Referring to Figure 9, Typical Relaying Characteristics on CCC Sheet, each half-circle with a handwritten time in seconds on the negative resistance side represents the worst-case motoring damage characteristic, based on $I^2t=3K$ and $I=1.732I_2$. For example, the half-circle with 120-second time stamp represents that 1 p.u. motoring current may require 120 seconds to damage the rotor pole surface.
- Referring to Figures 9 and 10, OOS Z1 means out-of-step zone 1, LOF Z1 means loss-of-field zone 1, and LOF Z2 means loss-of-field zone 2.
- Referring to Figure 10, Improved Relaying Characteristics on CCC Sheet, the time value in each parenthesis represents a directional phase overcurrent relay operating time.
- By plotting the negative-offset loss-of-field, single-blinder out-of-step, and one-step reverse-power relaying characteristics with typical settings on a CCC sheet (as shown on Figure 9, Typical Relaying Characteristics on CCC Sheet), ***it can be seen that certain severe synchronous/induction motoring will not be adequately protected***. ***The double cross-hatched area represents an unprotected zone for 30-second time delay setting*** and the single cross-hatched area represents an unprotected zone for 80-second time delay setting. To adequately protect against all severe motoring, it may be desirable to use the double-blinder out-of-step instead of single-blinder out-of-step, 2-step reverse-power relaying, and/or directional phase overcurrent relaying.
- CCC Sheet is primarily used for hydro-generators since the synchronous reactance of hydro-generators are approximately 1 p.u. on the machine base.
- Since a current magnitude really depends on the voltage magnitude for a given MVA, one CCC Sheet with both time-current characteristic and impedance relay characteristic cannot cover all cases. However, by selecting the worst case, one may be able to accomplish adequate coordination between all reverse power-related relaying schemes only with one CCC Sheet.

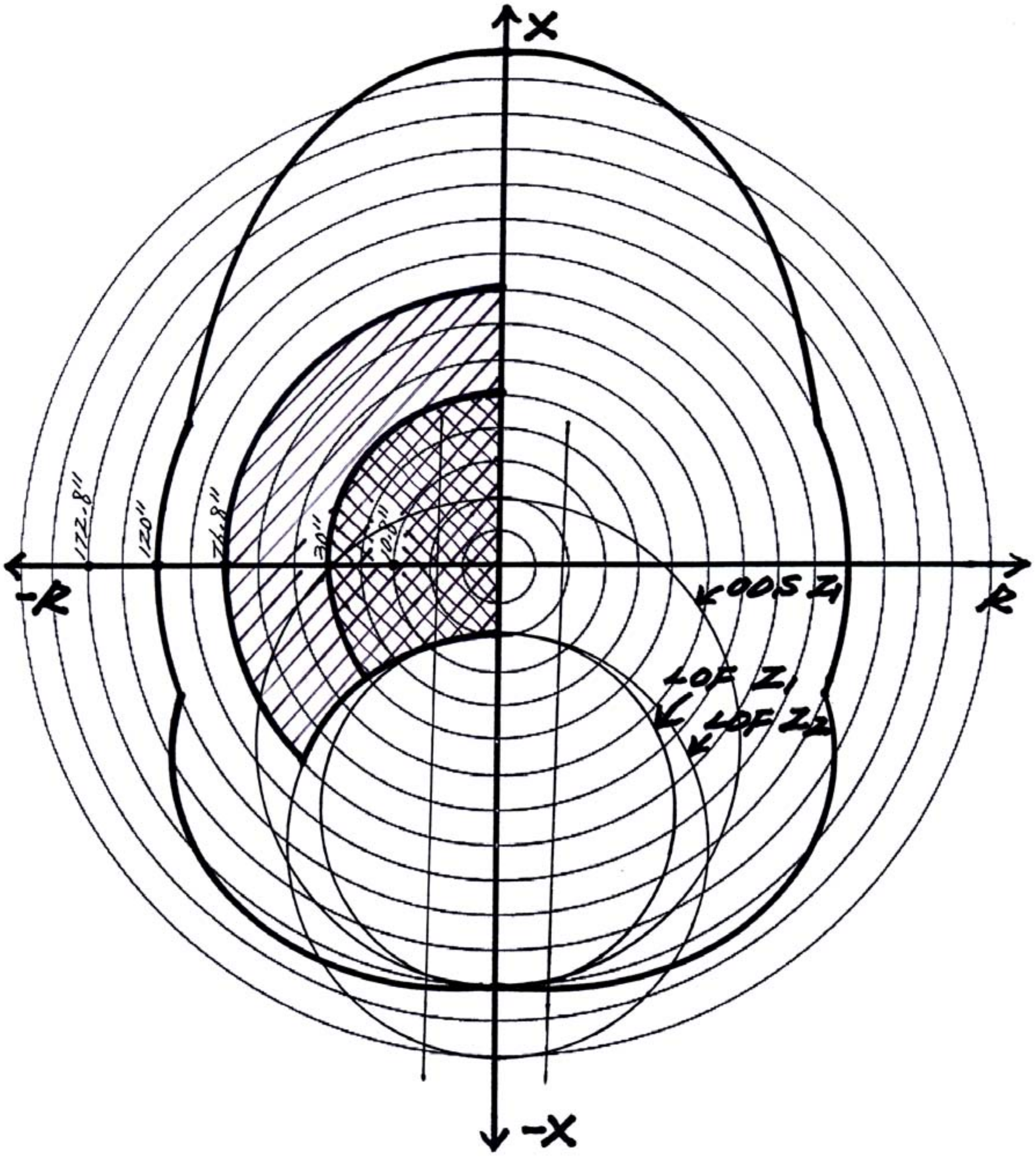

Figure 9. Typical Relaying Characteristics on CCC Sheet

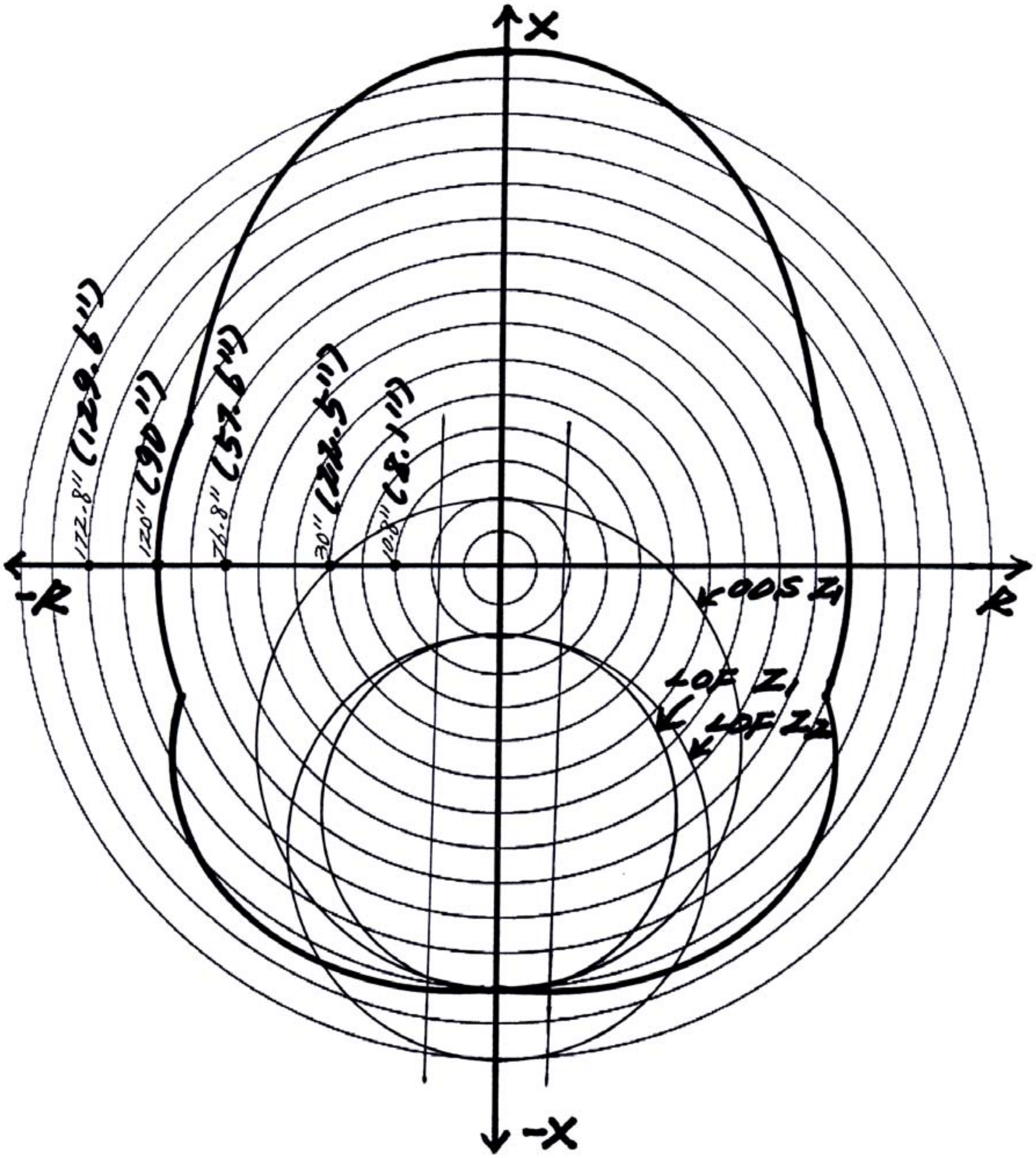

Figure 10. Improved Relaying Characteristics on CCC Sheet

VI. Conclusion

It is often said that nothing is perfect in this world. The imperfection of hydraulically controlled governor system and reverse power relaying in service has caused nuisance reverse power relaying operation problems more often than desired. To correct the nuisance operation problems, the author attempted to review reverse power relaying schemes from a relay application engineer's viewpoint and also to optimize our relay settings. The following is presented as a summary of author's current efforts to understand the reverse power relaying better and also to develop a better motoring protection scheme for hydro-generators:

1. The allowable reverse-power flow and acceptable duration for it are neither readily available nor easily deterministic.
2. The sluggish but normal governor operation is not adequately accommodated in reverse-power setting calculation so as to avoid nuisance operation problems.
3. Based on some of available data and test results, it appears that electrical damages seem to occur long before any serious mechanical damages and the mechanical strength of generators seems to be superior to electrical strength.
4. The traditional power-based reverse power relaying with a fixed time delay setting is primarily for mechanical damage protection against motoring because the amount of applied power is more directly related to mechanical damages than to electrical/thermal damages.
5. Thermal damages of the generator rotor result from the slip frequency current flow on the rotor pole surface and they are likely to occur long before any serious mechanical damages. Therefore, **a new current-based reverse power relaying with a variable inverse-type characteristic is more desirable for better electrical protection and less nuisance operation**.
6. Along with a new current-based reverse power relaying with a variable inverse-type characteristic, **$I^2t=3K$ and $I=1.732I_2$ for reverse power relay setting calculation can offer better reverse power protection against motoring.**
7. Generally, no coordination between all motoring protection schemes is attempted, so the unprotected motoring zone may not be obvious to application engineers. Use of the author's Concentric Circle Coordination Sheet may help application engineers accomplish adequate coordination between all motoring protection schemes.

The author sincerely hopes that this paper may be of some value to all WPRC attendees and help application engineers determine reverse power relay settings adequately in a practical manner.

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