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Generic Protection Model for Generator

Background

The NERC Plant-level Control and Protection Modeling Task Force (PCPMTF)[1] taskforce recommend that commercial software vendors adopt a model that can monitor and provide warnings of potential unit tripping due to synchronous generators encroaching on possible trip-zones of their protection systems.

Currently, a simple “generic” model of this nature exists in one commercial software tool (GE PSLF) called GP1/GP2 that can be expanded upon to facilitate adoption by all software platforms. This model has a basic representation of over- and under-voltage protections, over- and under-frequency protections, reverse power protection, and stator- and field-over-current protections. This model can be used to monitor generator models and warn the user if a generator appears to be entering regions of operation that may initiate a trip. The model can also be set to trip the generating unit. The PCPMTF task force recommended the development of an expanded version of this model, to be called GP3, to include the following:

- Over- and under-voltage protections,
- Over- and under-frequency protections,
- Reverse power protection,
- Field-over-current protections,
- Voltage Restrained Time Overcurrent relay,
- Loss of field protection,
- Turbine power/load unbalance protection, and
- V/Hz protection.

It is emphasized once more that the intent of this model is primarily to be used as a high-level screening tool (i.e. all functions in alarm mode) to draw the attention of a planner to potential issues that might exist with respect to a unit tripping on protection. Thus, subsequent analysis may be needed to look more closely at the actual protection settings of some specific units for a given study. As such, this model is high-level “emulation” of the most typical protective functions. It does not exactly represent any particular protective relay or function, nor is it a comprehensive representation of all possible protective functions at a synchronous power plant.

Also, it should be noted that this model does not include any of the typical limiter controls in most excitation systems, such as the over-excitation limiter (OEL), the under-excitation limiter (UEL) and the volts/hertz limiter. Needless-to-say, such limiter models may exist in commercial software tools and can be used. Also, clearly the intent and purpose of such limiters is to prevent the unit from encroaching trip-zones of the protective functions modeled here, such as the field overcurrent protection, and the V/Hz protection. Thus, if the OEL, UEL and V/Hz limiter are modeled, the protective functions in this model should be properly coordinated to avoid improper response.

A few other pertinent points are important to be made here:

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[1] http://www.nerc.com/comm/PC/PCPMTF_DL/Final_PCPMTF-Report.pdf

1. Modern digital generator protection packages, used on synchronous generators, can incorporate many functions from those mentioned above, to unbalanced overcurrent protection (46), out-of-step protection (78), breaker failure protection (50BF), and many more[2]. It is not possible to model all these various functions in a positive-sequence stability program, for various reasons. As an example, the unbalanced overcurrent protection function, simply cannot be modeled in positive-sequence simulations tools, where only the balanced conditions are modeled.

2. The protection functions proposed here for modeling, were judged by the PCPMTF, as being the most important for large-scale power system simulation studies. It must be understood that the simple generic model presented here is not all-inclusive and is not a representation of any specific generator protection system. It is a generic model intended to provide high-level monitoring for synchronous generators in order to indicate when generator protection might be likely to operate. Furthermore, there are many other potential layers of protection, which may lead under certain severe conditions, to a plant tripping, such as protection of auxiliary load. This model does not capture such protective devices. Therefore, the model is intended simply to be a tool for warning planners as to the potential for protection action at a plant and thus the need for more detailed analysis or review of the actual protection settings at a plant, if deemed necessary.

3. It should be noted that although the actual protective functions are standard across relays[3], how they are implemented exactly by each vendor, and at each site, can vary. For example, many implementations of V/Hz protection have more than one setting, where a larger setting is associated with a definite time delay for tripping, while a lower setting is used together with an inverse-time setting. Again, in the simple "generic" model proposed here, it is not possible to capture all such variations and possible settings. Thus, the functions are modeled in their simplest for, e.g. definite time V/Hz, etc.

GP3 Model Description

This document is a simple specification for the proposed GP3 "generic" synchronous generator protection model, which is an expanded version of the existing GP1/GP2 models. This model can only be applied to synchronous generators. The model is to contain the following functions and features:

- Over- and under-voltage protections – a simple function to detect over/under voltage with a definite time delay for tripping,
- Over- and under-frequency protections – a simple function to detect over/under frequency with a definite time delay for tripping,
- Reverse power protection,
- Field-over-current protections,
- Voltage Restrained Time Overcurrent relay,

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[2] For a detailed account of generator protection functions see the following references:
- IEEE Tutorial on the Protection of Synchronous Generators, 2011 (http://resourcecenter.ieee-pes.org/pes/product/tutorials/PESTP1001?source=IBP)
- http://www.nerc.com/comm/PC/System%20Protection%20and%20Control%20Subcommittee%20SPCS%2020/SPCS%20Gen%20Prot%20Coordination%20Technical%20Reference%20Document.pdf

[3] C37.2-2008 - IEEE Standard Electrical Power System Device Function Numbers, Acronyms, and Contact Designations http://ieeexplore.ieee.org/document/4639522/

- Loss of field protection,
- Turbine power/load unbalance protection, and
- V/Hz protection.

In addition, the model should have the following capabilities:

- to actually trip the generator model if one of the protection criteria are met, or alarm only without tripping the generator model,
- to be able to apply the model to (i) a single generator, or (ii) all generators in an area, or (iii) all generators in a zone, or (iv) all generators in the entire case,
- when the generator is tripped (or an alarm is generated without a trip), the model should write out to the simulation log-file the following information:
    - time of the trip/alarm
    - reason for the trip/alarm, e.g.
        - generator at bus 99999, with id 1, over-voltage protection picked up at time XXXX seconds since terminal voltage of 1.2 pu exceeded the over-voltage protection setting of 1.1
        - generator at bus 99999, with id 1, tripped (or [alarm only]) at time YYYY seconds since over-voltage protection timed out.

With the above in mind, below is the definition for the implementation of these protection functions proposed by the PCPMTF, for the so-called GP3 model. Table 1 shows the list of parameters for the model. The first two parameters, *flag1* and *flag2* are self-explanatory. With the exception of the power/load unbalance function, the loss-of-field function, voltage-restraint inverse-time over-current trip function and the over-excitation trip function, all other features of this model are identical to the existing GP1/GP2 models in GE PSLF, as recommended in the PCPMTF document. The difference in the over-excitation trip function is that it has now been made into a simple definite time trip setting, rather than a "generic" inverse time trip. This is because, most over-excitation limiters (OELs) on synchronous generators tend to be inverse-time, or have several pickup points (e.g. an inverse-time setting and a hard definite-time setpoint at a higher level), and may not even have a trip setting. So, a simpler definite time model is likely adequate.

To fully define the model the following is provided:

1. **V/Hz** – in actual relay equipment the calculation is typically based on terminal voltage and frequency. To avoid complications with calculating terminal frequency, for modeling purposes, this can be implemented as follows:

    If $(Vt/\omega) > vhz$ for *tvhz* seconds, then alarm (or trip) the unit, where *Vt* is the generator terminal voltage, and ω is the generator speed. If V/Hz returns below the trip point prior to the relaying timing out, the timer is reset.

2. **Over/Under-voltage** – this is modeled by a simple, single, definite time setting. Actual real equipment may have multiple settings. The logic for the model is as follows:

    If $Vt < vuv$ for *tuv* seconds, then alarm (or trip) the unit, where *Vt* is the generator terminal voltage.
    If $Vt > vov$ for *tov* seconds, then alarm (or trip) the unit.
    If *Vt* returns above (below) the trip point prior to the relaying timing out, the timer is reset.

3. **Reverse Power** – the logic for this function is as follows:

   If $Pgen < pmtr$ for $tpmtr$ seconds, then alarm (or trip) the unit, where $Pgen$ is the generator terminal electrical power. If $Pgen$ returns above the trip point prior to the relaying timing out, the timer is reset.

4. **Loss-of-field** – the most common LOF relay is the offset mho relay with two zones. This is shown in Figure 2. The most typical values for the settings are shown in Table 1. Thus, this relay can be modeled as follows:

   First the generator apparent impedance (on generator MVA base) is calculated at every time step, i.e. $Zgen = Vt/It$ (complex values) = $R_{gen} + jX_{gen}$

   If $Zgen$ enters Zone 1 (i.e. $R_{gen}^2 + (X_{gen} - Xoff + Xz1/2)^2 < (Xz1/2)^2$) for $tz1$ seconds, then alarm (or trip) the unit. If $Zgen$ exits Zone 1 before the relay times out, then reset the timer.

   If $Zgen$ enters Zone 2 (i.e. $R_{gen}^2 + (X_{gen} - Xoff + Xz2/2)^2 < (Xz2/2)^2$) for $tz2$ seconds, then alarm (or trip) the unit. If $Zgen$ exits Zone 2 before the relay times out, then reset the timer.

   If the model is instantiated on a single generator, then the user may specify the values for $Xz1$, $Xz2$ and $Xzoff$. If either Xz1 or Xz2 is entered as “zero”, then the model will use the default values of $Xz1 = 1$ pu, $Xz2 = Xd$ (read from the generator dynamics model) and $Xoff = -X'd/2$ ($X'd$ read from the generator model), all on the generator MVA base. If the model is instantiated to be effective at the Zone/Area/All-units level, then the values of Xz1, Xz2 and Xzoff are internally set to the default values, i.e. $Xz1 = 1$ pu, $Xz2 = Xd$ (read from the generator dynamics model) and $Xoff = -X'd/2$ ($X'd$ read from the generator model), all on the generator MVA base. This model must be used in conjunction with the higher order generator dynamic models, e.g. GENROU, GENROE, etc. which include Xd and X’d. If the GP3 model is instantiated on a unit using a GENCLS a warning message should be displayed indicating to the user that the GP3 model has ben disabled and is being neglected, unless the user employees are more appropriate generator model.

5. **Over-excitation** – the over-excitation protection is modeled with a simple definite time model. That is:

   If $Ifd > ifoc$ for $tfoc$ seconds, then alarm (or trip) the unit, where Ifd is the generator field current. If the field current returns below the trip point prior to the relaying timing out, the timer is reset.

6. **Power/Load Unbalance** – the power/load unbalance protection typically resides in the turbine controls and is used on large steam-turbines. Typically, actual power/load unbalance protection works by measuring the electrical load of the generator from the generator terminal PT/CTs and the power being developed by the turbine from the combined pressure signals from the turbine stages. For simplicity, in this generic model the electrical load is taken to be the generator power ($Pgen$) and the power developed by the turbine is taken directly from the turbine-governor model output ($Pmech$). The protection logic is then:

   If $(Pmech - Pgen) > delp$ for $tdelp$ seconds, then alarm (or trip) the unit. If the $(Pmech - Pgen)$ goes back below $delp$ before the relay times out, then rest the timer.

7. **Over/Under-frequency** – this is modeled by a simple, single, definite time setting. Actual real equipment may have multiple settings. The logic for the model is as follows:

   If $\omega > fof$ for tof seconds, then alarm (or trip) the unit, where ω is the generator speed. Speed is used instead of calculated frequency, to avoid problems with frequency calculation in positive-sequence stability programs.

   If $\omega < fuf$ for tuf seconds, then alarm (or trip) the unit.

   If ω returns below (above) the trip point prior to the relay timing out, the timer is reset.

   If $Vt < 0.7$ this relay function is disabled, until voltage comes back up above 0.75 pu.

8. **Voltage Restrained Time Overcurrent**– this relay is modeled with a simple, and generic, voltage-restraint time-overcurrent relay model. It is slightly different to the existing feature in the GP1/GP2 models in GE PSLF, in that the model proposed here is based on the IEEE standard characteristic of an inverse-time overcurrent relay[4], rather than being completely generic. IEEE C37.112 provides the following equations for the relay trip time:

$$T_{trip} = \left(\frac{koc}{\left(\frac{|It|}{ipickup}\right)^{poc} - 1} + boc \right) \tag{1}$$

The optional reset rate of the relay timer, which is included here, is given by the equation

$$T_{rest} = \frac{troc}{\left(\frac{|It|}{ipickup}\right)^{2} - 1} \tag{2}$$

Here $|It|$ is the magnitude of the stator-current in pu. The relay then operates under the following premise:

Trip = 0 (internal variable of the model)

$$Trip = \int_{o}^{t} \frac{1}{T(It)} dt \tag{3}$$

where

$$T(It) = \begin{cases} T_{trip}(It) \text{ if } |It| > ipickup \\ T_{rest} \text{ if } |It| < ipickup \\ -troc \text{ if } |It| = ipickup \end{cases}$$

Thus, *Trip* is continuously integrated from time *0* to time *t* in the simulation, and the relay alarms (trips) the unit, if and when *Trip* = 1. The pickup current *ipickup*, is determined as shown in Figure 2, based on the user input parameter *ioc*, and a hardcoded voltage-restraint function. The voltage restraint function proposed here is again slightly different to the existing GP1/GP2 models in GE PSLF, but it is based on what is implemented in many relays.

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[4] C37.112-1996 - IEEE Standard Inverse-Time Characteristic Equations for Overcurrent Relays

Table 1: Parameters of GPS (all [pu] quantities should be on the generator MVA base)

Parameter	Description	Typical Range/Value	Units
flag1	0 – alarm only; 1 – trip generator	0 – typically use to alarm only and not trip generator model	N/A
flag2	1 – monitor generator; 2 – monitor all generators in area; 3 – monitor all generators in zone; 4 – monitor all generators in the entire case	N/A	N/A
vhz	V/Hz trip setting	1.1 – 1.20	[pu]
tvhz	Definite time trip for V/Hz	2 – 6	[s]
vuv	Under-voltage trip setting	0.8 – 0.89	[pu]
tvuv	Definite time trip for UV	1 – hundreds	[s]
vov	Over-voltage trip setting	1.1 – 1.2	[pu]
tvov	Definite time trip for OV	Fraction of a second - 2	[s]
pmtr	Reverse power trip setting	-0.005 to -0.08 (larger values on GTs; smaller for STs)[5]	[pu]
tpmtr	Definite time trip on reverse power	10 – 20	[s]
Xz1	Loss-of-field Zone 1 impedance[6]	1	[pu]
Xz2	Loss-of-field Zone 2 impedance	Xd	[pu]
Xoff	Loss-of-field impedance off-set	-X'd/2	[pu]
tz1	Definite time trip for Zone 1 of LOF	0.05 – 0.1	[s]
tz2	Definite time trip for Zone 2 of LOF	0.5 - 1	[s]
ioc	Stator Over-current trip pickup setting	1.05 – 1.2	[pu]
koc	Time factor for over-current trip	N/A (moderately inverse = 0.0515)	[s]
boc	Timer coefficient for over-current trip	N/A (moderately inverse = 0.114)	[s]
poc	Exponent for inverse-time	0.02 - 2	N/A
troc	Reset time for over-current relay	4 – 29	[s]
fof	Over-frequency trip setting	1.02 – 1.05	[pu]
tof	Definite time trip for OF	1 – 2	[s]
fuf	Under-frequency trip setting	0.96 – 0.98	[pu]
tuf	Definite time trip for UF	1 – 2	[s]
delp	Delta power Imbalance for Power/Load Unbalance Relay	0.3 – 0.4 (used only typically for large STs)	[pu]
tdelp	Definite time trip for Power/Load Unbalance	1 – 2	[s]
ifoc	Over-excitation trip setting	N/A	[pu]
tfoc	Definite time trip for over-excitation	N/A	[s]

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[5] The reverse power settings for various types of generation equipment can be quite different. This should be taken into consideration, when setting the values for the reverse power relay, or interpreting the results is a blanket value is used to model the protective device over an entire area or zone.

[6] Typical settings for LOF relay are from WG J-5 of PSRC report, "Coordination of Generator Protection with Generator Excitation Control and Generator Capability", Proceedings of the IEEE PES GEM 2007.

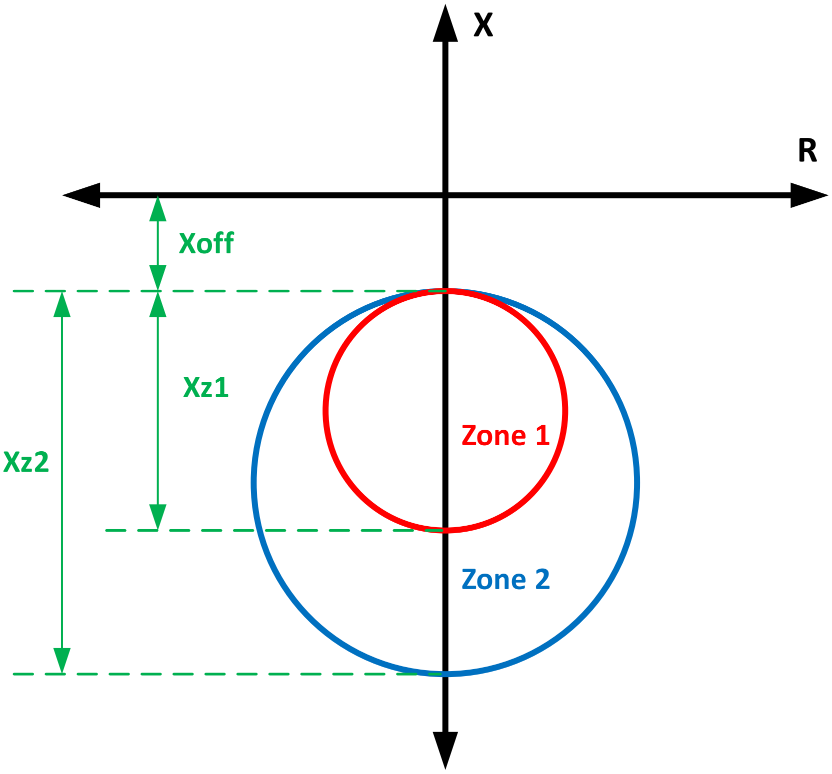

Figure 1: X-R diagram showing the characteristics of the offset-mho type loss-of-field relay.

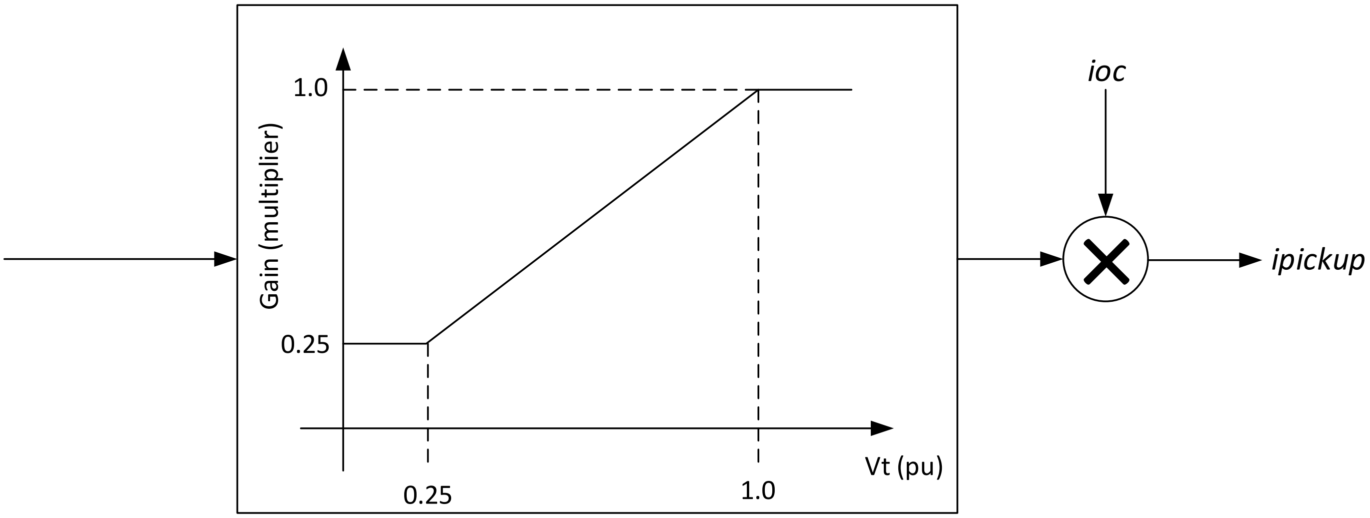

Figure 2: Hardcoded voltage-restraint function in the inverse-time over-current relay.