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Constraints and Optimization in Line-Powered Fault Interrupters

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SUMMARY

Over the last few years, we have seen a new generation of highly integrated single phase lateral reclosers in the market. They have proved to provide tremendous benefit to the utility companies in terms of reliability, yet their differences in performances are not fully understood. In this paper, we will explain the most common power supply architectures used in such devices, and how they impact protection capabilities, weight, reliability, and cost.

KEYWORDS

Line powered recloser, single phase lateral, energy harvesting current transformer, voltage across VI harvesting

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INTRODUCTION

In the last few years there has been an explosion on the number of new single phase lateral reclosers in the market [1][2][3], and for a good reason; reports from the DoE show significant reduction in SAIDI and SAIFI indices when these products are deployed system-wide [4][5].

These types of reliability improvements are expected for two main reasons:

- Exposure: Laterals cover more miles than feeders, and therefore they experience more faults per year than at the feeder level.
- Maintenance: Laterals' maintenance cycle is lower than the one for the main feeders, increasing their likelihood of being subjected to faults. For instance, FPL's tree trimming cycle is 3 years for feeders and 6 years for laterals [6]

Single phase reclosers are not a new concept, but this new generation of single phase lateral reclosers bring levels of integration and simplicity never seen before. These type of new reclosers include the interrupting system, power supply, relay, as well as, in most of the cases, local communications in one package. Such levels of integration make these devices very attractive for utilities since they are cost effective, easy to deploy, and require low maintenance in most cases.

The purpose of this paper is to explain key differences between the different architectures, so users of these devices can understand the pros and cons of each design. We will pay special attention to the power supply since that is where the main differences in performance will reside.

LINE POWERED FAULT RECLOSER ARCHITECTURE

A typical architecture used in the next generation line powered fault recloser can be seen in Figure 1. Most of the line powered fault recloser designs use a current transformer (CT) as the primary source of energy to charge an energy storage capacitor. That energy is then used to drive the VI's actuator and to power the low voltage electronics, including communications and the processor performing the relay functions.

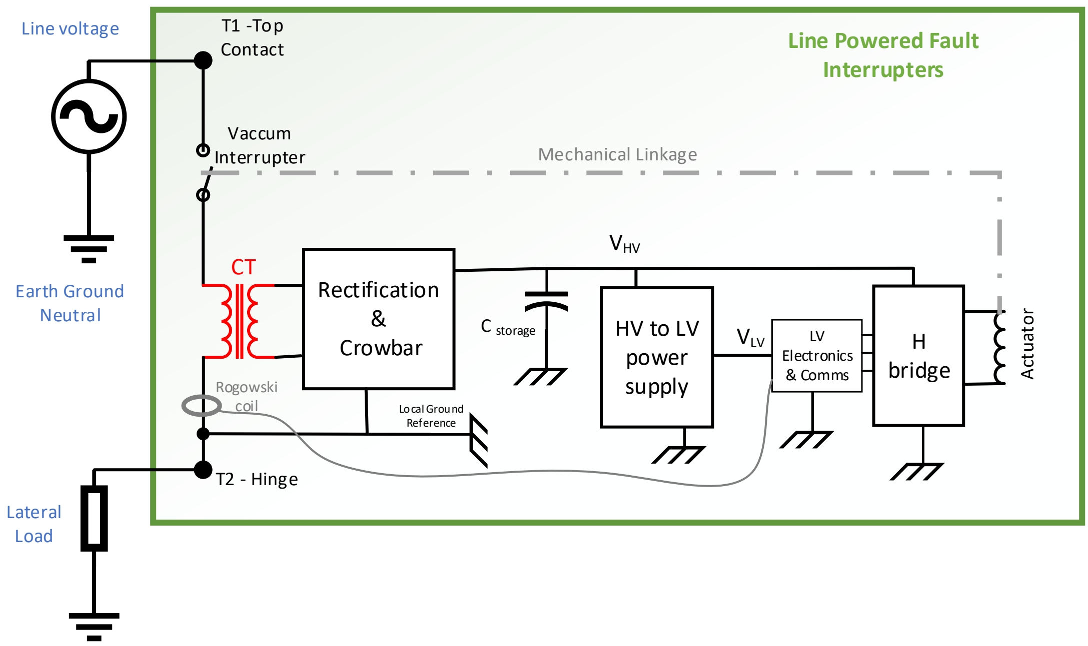

Figure 1 Typical architecture of next generation of line powered fault interrupters

The main blocks are:

- CT for energy harvesting
- Rectifier to convert the AC to DC so it can be stored in an energy storage capacitor.
- Actuator driver to open and close the magnetic actuator
- Current sensing
- Magnetic actuator
- Vacuum Interrupter

We will focus mainly on the power supply/energy harvesting subsystem for two reasons:

1. All other subsystems are well-defined and understood given the ratings of a unit. For instance, if a single phase lateral recloser is rated 8kA-15.5kV, it is possible to find an off the shelf vacuum interrupter (VI) that will be able to perform at such ratings. Given the VI, the size and energy requirements of a magnetic actuator is also given.
2. The recloser's key performance differentiators depend heavily on the energy harvesting subsystem, since that will dictate the following features:
    - Cold start characteristics
    - Minimum current to power up
    - Longest opening interval
    - Maximum number of reclose sequences it can perform

The main component of the energy harvesting subsystem is the CT. Its size, and therefore cost, will dictate what type of performance you can expect from the single phase recloser.
In the following section we will explain 3 different designs of the CT, but first we need to define the CT requirements and how they affect the design parameters

POWER SYSTEM REQUIREMENTS AND DESIGN PARAMETERS

When comparing single phase lateral reclosers, protection engineers usually look at the following items:

- Cold start: This refers to the ability of the device to respond to faults that take place when the energy storage starts from a completely depleted state. In other words, it tells you how the unit will respond from a dead start and if it can mimic a fuse response for any load current condition prior to a fault. This scenario is more typical than we think, since laterals can have very low load conditions where no reasonable sized CT will be able to harvest energy. It is common practice to specify the cold start performance of a CT using terms like charging time expressed as X/current. For instance, a 10/current cold start, will mean that a fault current of 300A could be cleared in around 2 cycles by the recloser. Such characteristics can be plotted as a TCC to make sure coordination is possible even under the worst-case scenario.
- Minimum wake-up current. This is the minimum current required to be able to power up the low voltage energy. Some manufactures will differentiate between powering up just the relay and powering up the relay + communications
- Nominal current and Fault current withstand. This parameter will have a direct impact on the CT wire gauge of the CT, since it will have to carry such current
- Opening Interval and number of intervals.

We now have a picture of the type of power system requirements the protection engineer is looking at. Such requirements will have a direct impact on the size and cost of the CT, as well as the cost of the electronics attached to it.

Given the power system requirements (cold start equation, minimum wake-up current, nominal current, opening interval, etc.) and the electronics, as well as actuator requirements (energy to drive the actuator and power to keep the electronics alive), the design the CT is straight forward. Here you have the three steps:

1. Determine the turn ratio of the CT, by knowing your cold start characteristic
2. Determine the core cross section of the CT, but knowing the type of steel you want to use (by knowing what is the maximum magnetic field of the core's steel)
3. Determine the overall size of the CT by including the wire gauge you will be using for the different windings.

We need to remember, that these are energy harvesting CT, and they are normally not used for measurements. Once the CT is sized, the electronics connected to it need to be sized appropriately. They will be responsible for shorting the CT when enough energy has been harvested.

CT DESIGN COMPARISON (IMPACT OF WEIGHT AND SIZE)

In general, we can say that there are three possible versions of energy harvesting subsystems for line powered reclosers. We will compare all three in terms of size, power electronics requirements, reliability, and system performance.

Energy harvesting subsystem with cold start capabilities

For this design, we will assume the current transformer is the only source of input energy with cold start capabilities. This design leads to a design with the highest performance at the cost of larger CT and expensive power electronics.
The principle of operation is the following:

- At t0, we assume the unit has been without powered for long time, that is, the line current is very low to power up the unit in any way.
- At t1, the fault takes place and CT starts charging the energy storage cap.
- At t2 the control issues the open command.
- At t3 the VI opens and clears the fault. From this point on the unit can no longer harvest energy from the CT and it will stay alive from whichever energy has within the control
- At t4 the control devices to reclose as part of the reclose sequence
- At t5, the VI closes, but in this case the fault is still present.
- At t6, the unit has charged just enough to open
- At t7, the unit locks out.

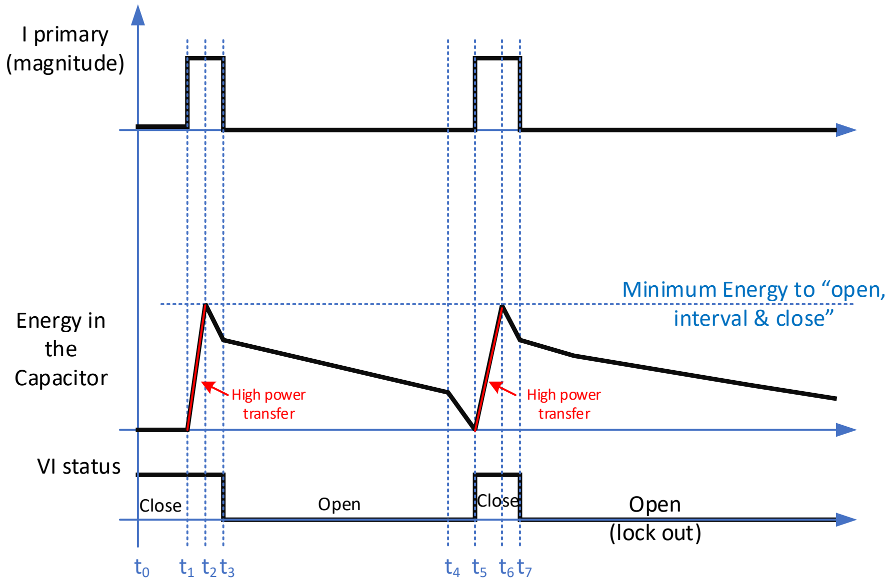

Figure 2. Energy profile when using a CT with cold start capabilities

As we can see, the CT needs to be large, since it needs to transfer significant amount of power within one cycle (from t1 to t2 and from t5 to t6) to meet the cold start performance and coordinate with upstream devices, and to mimic fuses response.
Here you have an example. Let us assume the following:

- Electronics and actuator need 10 J to be able to do from t2 to t5.
- Cold start characteristic of: Trip time (seconds) = 10/ Fault Current (Amps).

Such CT needs to be able to transfer an average of 600Watts in 1 cycle for fault current higher than 600A. The CT will weigh around 6 lb., and the electronics connected to it (rectifier and crowbar) will be expensive due to the high-power dissipation requirements (CT ratio will low, meaning high secondary currents) coupled with high voltage conditions.
This design has the best performance (unlimited number of reclosing attempts and being able to coordinate with devices under any load condition) however there is a trade-off of high cost and weight.

Energy harvesting subsystem without cold start capabilities

For this design, we will assume the current transformer is the only source of input energy. Such CT will not provide cold start capabilities, but it will be large enough to trickle charge the energy storage caps and keep the low voltage electronics alive.
The principle of operation is the following:

- At t0, we assume the unit has been powered for long time, and therefore the energy storage capacitor is fully charged. We are assuming the load current is high enough to power up the unit.
- At t1, the fault takes place
- At t2 the control issues the open command
- At t3 the VI opens and clears the fault. From this point on the unit cannot longer harvest energy from the CT and it will stay alive from whichever energy has within the control
- At t4 the control devices to reclose as part of the reclose sequence
- At t5, the VI closes, but in this case the fault is still present.
- At t6, the unit locks out

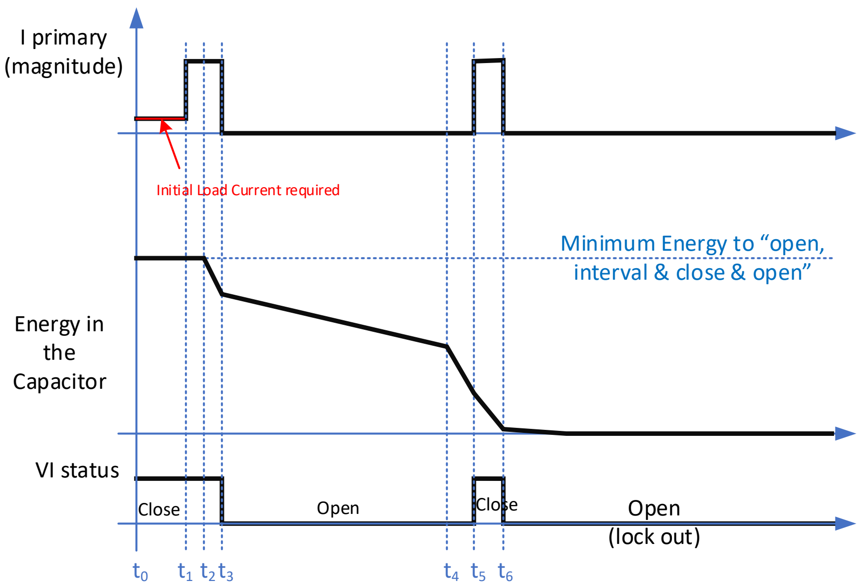

Figure 3 Energy profile when using a CT without cold start capabilities

The key requirement for this design to work is that the unit needs to be powered for quite some time (even minutes) before it can perform any function. Special attention needs to be paid to what the minimum input current requirement is to fully charge and keep the unit alive. In some designs, it is possible to find the option of batteries to keep the unit alive for long periods to overcome such restriction with low load conditions. However, as one can expect adding batteries reduces the reliability of the product.
Also, this type of design has the limitation of a very low number of reclosing attempts, since the energy storage capacitors will have to be sized to hold enough energy to be able to perform the entire sequence, including the opening interval. Usually, these devices are restricted to just one reclose event.
Here you have an example. Let us assume the following:

- Low voltage electronics require less than 0.5Watts to run
- Trickle charge of the energy storage caps (in the minutes range)

Such CT will weigh around 2 lb., and the electronics connected to it (rectifier and crowbar) will be inexpensive since such CT will easily saturate at high currents and it has low power transfer capability (meaning its turn ratio will be high and therefore the secondary current will be very low, reducing the power electronics requirements).
This design is very economical, but it has severe performance limitations.

Energy harvesting subsystem without current transformer

It also possible to find single phase lateral recloser powered using other type of energy harvesting subsystems, like

- Photovoltaic with supercapacitors complemented with batteries. For this type of technologies, special attention will need to be paid to reliability over the life of the product.
- Voltage powered reclosers. These type devices are not line powered, and they require a ground reference during installation as well as surge arresters. Their architecture is more conventional and typical of three phase reclosers. Voltage powered reclosers usually use ceramic capacitors as insulators and current limiting components. Special attention needs to be pay to their BIL performance and lifetime.

For this type of reclosers, the principle of operation is like the one with the trickle charge CT; they do not have any cold start properties. However, they do not depend on the load current to power up.

Comparison

The table below shows a comparison of the different designs.

Feature	Cold Start CT	Trickle charge CT	Energy harvesting without CT
Cold start*	Yes	No	Yes
Weight	Heavy (6lb)	Light Weight (2lb)	Light Weight
Electronics	High Power	Low Power	Low Power
Cost	High Cost	Low Cost	Low cost
Reliability	High	High (if no batteries)	Medium/Low

*Ability to mimic a fuse response under any load current condition prior to the fault event

CONCLUSION

The new generation of fully integrated line powered single phase reclosers bring great benefits to electric utilities by increasing the system's reliability. However, special attention needs to be paid to their capabilities. Protection engineers need to understand what type of protection coverage they need from these types of devices, since it determines unit's response capabilities and their size/weight, which ultimately drives adoption of the solution and a successful outcome for the investment

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