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Innovative and Effective Method and System for Voltage Improvement, Power Quality and Reduction of Losses in Electrical Power Distribution

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SUMMARY

Both the electric utilities and end users of electrical power are becoming increasingly concerned about the quality and efficiency of electric power. The issues that are related to power quality and efficiency are not necessarily new and are addressed in many ways. Traditional methods can be quite expensive requiring major reconstructions, long duration of construction, large capital investment with long term returns and public hearings.

This paper addresses the above through an integrated approach of theory and practice combined with an innovative and patent pending Method and System which led to the development of the Medium Voltage Regulating and Optimizing Terminal “MVROT”. The unit will address power distribution energy inefficiencies by providing improved power quality through the implementation of simple and cost-effective technology to reduce losses, improve voltage at the load centres, add grid selectivity, and eliminate harmonics in the system.

This technology creates an adaptive infrastructure within the existing or new distribution grids, that will increase customer satisfaction, reduce outages, improve/increase safety and reliability and it is virtually maintenance free. Easy and fast implementation of this system within the existing grids will resolve any issues in medium voltage distribution networks, quickly and without long power outages.

This Method and System paired with MVROT technology is being planned for implementation in a Pilot Project within one of the major distribution company in Western Canada to collect data before and after the introduction of the MVROT. Results from the Pilot Project are expected to be available immediately after installation. Based on the above, Project objective is to compare all data and results between measured and recorded data, before and after MVROT implementation as per EN 50160 standard, proving power quality improvements within existing grids. This technology along with its benefits, and field verification results will not only be available for Canada but Globally as well.

When implementing this system to the entire distribution network, reduction in the power distribution losses could be up to 60% and voltage drop reduction up to 40%. Partial implementation will reduce these savings and this Pilot Project is expected to reduce power losses in the range of 20%.

KEYWORDS

Efficient distribution network, Safety, Reduction of power losses and voltage drops, Innovative technology, Grid selectivity, Reduced possible power outages, Harmonics, Grid Automatization.

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1. INTRODUCTION

According to the Canadian Electricity Association and Infrastructure [4], the Canadian electricity sector is expected to spend approximately $294 billion on aging infrastructure between 2010 and 2030. Many Canadian utility companies see this as the single biggest challenge to their operations and their capital spending plan. As the condition of the infrastructure continues to deteriorate and load continues to grow, power quality, transmission, and distribution efficiency, Green House Gasses "GHG" and safety become more of a concern for not only the utilities but also the industrial and residential consumers.

New, green generating power technologies are tapped into the existing grids and with that they are bringing additional challenges to the overall distribution grids. DC to AC convertors are adding big harmonics into the systems. North American three phase distribution grids with single phase tap in branches creates unbalanced loads within three phases and neutral wire is needed to close circuits. Distribution grid efficiencies in urban versus rural areas is presenting a problem as well. Small number of consumers far apart in rural areas requires big investment but small to no return.

This new technology presented here is addressing existing and new distribution grids inefficiencies, increasing reliability and resiliency, reducing possibilities of outages, increase safety - eliminating current [A] flow in the neutral wire by making balanced loads between phases, eliminates harmonics at the primary sides toward the main substation, reducing energy losses and voltage drops, maintenance free and is environmentally friendly.

2. COMPARISONS BETWEEN TRADITIONAL / CLASSIC DISTRIBUTION GRID RECONSTRUCTION SOLUTIONS VERSUS MVROT METHOD AND SYSTEM

Traditional and classic methods available today, up to now, to improve delivered power quality within the existing grids are:

a) Changing the entire grid to the higher voltage levels. This is a big capital investment, as the entire infrastructure and equipment would need to be replaced, a new substation with higher secondary voltage levels built, and lengthy construction time leaving consumers without power or quality of power until reconstruction is done. This method is effective but requires public hearings and taxpayer funding, resulting in an increase of $/kWh to recover the capital investment. Regardless of the type of funding this method would bring significant financial stress to distribution companies and to the end users with investment return being very long. This method still does not address harmonics, unbalanced loads or grid selectivity.

b) Changing phase conductors and neutral wire cross section to bigger sizes. This would add additional loads onto the existing poles which might need to be replaced. Less investment needed than the first option but still does not address all issues. Due to some limitations in wire spans consumers on the end of the long distribution line (rural areas) might still lack quality of power as voltage levels might still be below standard.

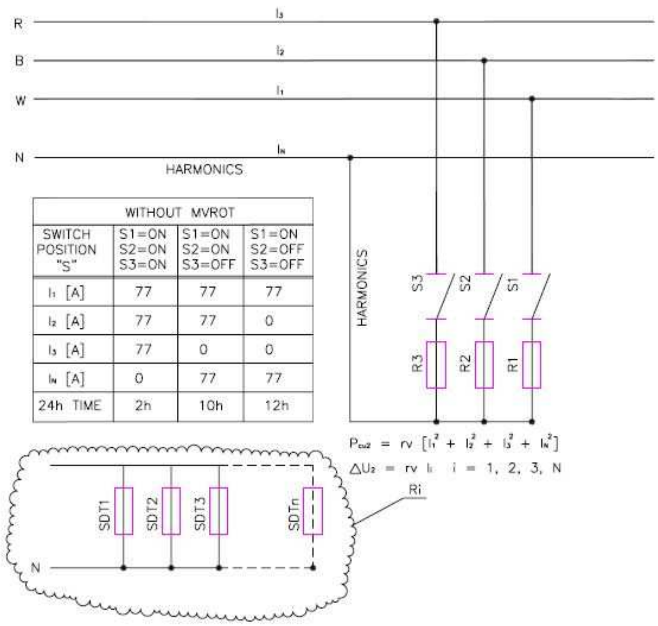
c) Changing conductor's cross sections and adding capacitors is an expensive solution and there is a possibility for overvoltage in the system within the long lines.

New method and system with MVROT implementation presented in this paper has an innovative solution in comparison to traditional methods. All the issues named above can be solved at once, with fast and simple installation, small investments, efficient grid, smaller currents [A] within phases, reduced losses and voltage drops, balanced loads, no current in neutral lines, eliminate harmonics, add grid selectivity (localize possible faults), maintenance free, dry technology and environmentally friendly.

Quick investment return as the unit pays for itself by significant reduction in power losses allowing power providers to have more energy to deliver and collect more revenue.

3. TYPICAL DISTRIBUTION SCHEMATIC WITHOUT MVROT

Figure 1



WITHOUT MVROT			
SWITCH POSITION "S"	S1=ON S2=ON S3=ON	S1=ON S2=ON S3=OFF	S1=ON S2=OFF S3=OFF
I_1 [A]	77	77	77
I_2 [A]	77	77	0
I_3 [A]	77	0	0
I_N [A]	0	77	77
24h TIME	2h	10h	12h

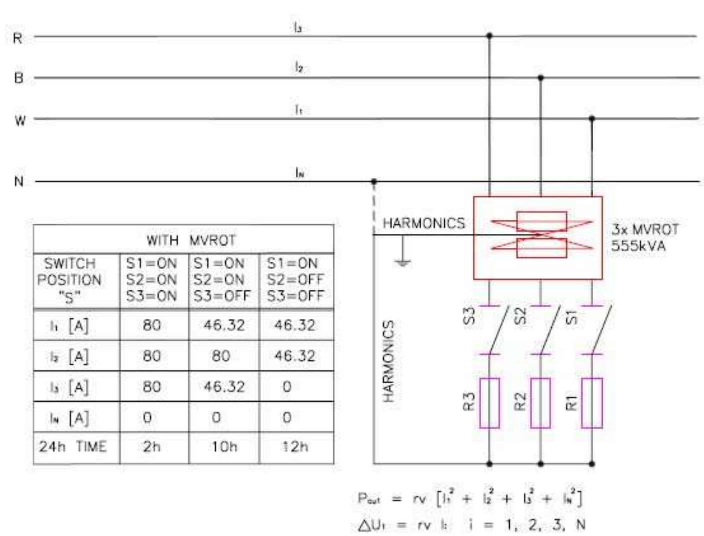
In a medium voltage distribution system and depending on requirement and operation condition, 3 Phase 3-wires or 3 Phase 4-wires could be used. If a large amount of power is to be distributed and the demand is constant on all phases, a 3 Phase, 3-wire system would be preferable and more economical, as a result of the savings in material cost and construction of the 4th wire along with the losses in that wire. Generally, on the distribution side, a 3 Phase 4-wire system is preferable, yet if the load is industrial loading (Mainly balanced Induction Motors) 3 Phase 3-wires is used. In an unbalanced load distribution loads, in a 3 Phase 4-Wire system, the unbalanced current path and flow is through the fourth or neutral wire.

The current in the neutral wire presents a public safety concern and is considered to be a pure loss in the distribution systems. The Harmonics generated by the end users are transferred from the load side to the source through the neutral wire where it requires a very expensive harmonic filter or regulator with its own associated control system.

"Figure 1" shows a typical distribution schematic cycle during a 24h period.
When all loads (switches) are connected, the system is balanced and no current [A] is flowing through the neutral wire. This scenario is very short and in average could last about 2 hours. As soon as one of the switches is in the "off" position, then current [A] flows through the neutral wire to balance loads. These scenarios in distribution grid are present most of the time, about 22h in total.

3.1 TYPICAL DISTRIBUTION SCHEMATIC WITH MVROT

Figure 2



WITH MVROT			
SWITCH POSITION "S"	S1=ON S2=ON S3=ON	S1=ON S2=ON S3=OFF	S1=ON S2=OFF S3=OFF
I_1 [A]	80	46.32	46.32
I_2 [A]	80	80	46.32
I_3 [A]	80	46.32	0
I_N [A]	0	0	0
24h TIME	2h	10h	12h

Implementing this new Method and System together with the MVROT terminal for the balancing loads in each phase in medium voltage distribution systems and utilizing special system analysis methodology that identifies the optimal location in an existing gird to insert one or more MVROTs brings many benefits.

MVROT insertion reduces or totally eliminates neutral and circuit currents in the main grid and ground on primary side, significantly reduce overall energy losses and voltage drops.

“Figure 2” shows a typical schematic cycle diagram as “Figure 1” with MVROT tapped to an existing 3 Phase 4-wire 4160Y/2400 Volt feeder, complete with a table showing the various connection scenarios and each result. For any switch position current [A] is always equal to zero (0) in neutral wire at primary side. The purpose for the neutral wire at the primary side is for extra grounding and protection.

Any harmonics generated on the secondary side of MVROT are eliminated / dissipated within the unit, preventing them from being transferred to the primary side (main feeders). With MVROTs installed at all load centers they can completely eliminate harmonics from the main substation and with that eliminate needs for the big harmonic filters within that station.

Additional benefits to Utilities due to this inherent design include improved ability to isolate sections of the feeder providing enhanced fault detection, safety and protection.

This paper shows calculated results specifically in the “3 Phase 4-wire 4160Y/2400 Volt feeder" as the results to be confirmed from the planned Pilot Project within the distribution grid in Canada. Other voltage levels (25/14.4 kV, 13.8/7.96kV…) are having the same principles as what is presented here.

4. MVROT METHOD AND SYSTEM AND MVROT WORKING PRINCIPLE

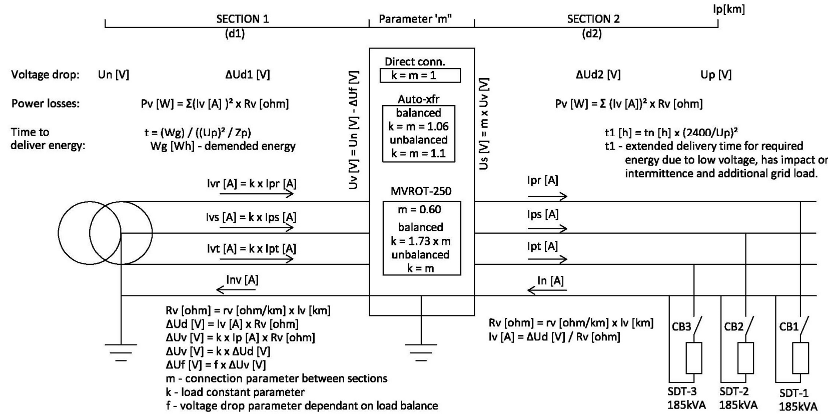
To explain the working principle of this method and system and MVROT, “Figure 3” is showing, three phase Distribution Network Grid (“DNG”) that is divided into two sections (“SECTION 1” and “SECTION 2”). The connection between those two sections is defined by parameter “m”. Depending on possible connection types between these two DNG sections, values of parameter “m” are:

m=1 – direct connection, where SECTION 1 and SECTION 2 are connected by the same conductor(s) size(s) and characteristics as both sections are made of.

m=1.06 and m=1.1 – represent autotransformer connection. SECTION 1 and SECTION 2 are connected through autotransformer to compensate voltage drops in SECTION 1. This is classical connection to uplift voltage using various numbers of windings within autotransformer to change parameter “m” and with that uplift voltage for SECTION 2 to compensate voltage drop in SECTION 1. Increasing value of parameter “m” can be automated and it is possible to get that value up to 2.

m=0.6 – This is MVROT connection (MVROT is not autotransformer). This connection through MVROT, that has constant parameter m=0.6, between SECTION 1 and SECTION 2 allows loads to be balanced within phases and these smaller and balanced loads per phase achieve smaller voltage drop in SECTION 1. With the smaller voltage drop in SECTION 1, SECTION 2 has better voltage to start with and with that better power quality on its end.

Figure 3



Distribution loads per phase are constantly changing and is a factor that cannot be controlled. This uncontrolled process is defined by the level of balance between loads in phases. There exist two different scenarios in the grid which can be identified.

- Balanced loads in DNG. The loads per phase are balanced and no currents [A] (loads) are flowing through neutral wire. In = 0.

- Unbalanced loads in DNG. Each phase is not simultaneously balanced, which results that current [A] (load) is flowing through neutral wire. In>0. During time of maximum unbalanced loads, current in neutral wire can be equal to current in phase conductor.

During the Engineering phase and after commissioning of DNG, significant attention must be focused toward "STABILITY" of the grid, considering optimal investments and economics at the same time. The term STABILITY is referring to the commissioned and energized grid able to withstand maximum balanced and unbalanced loads that can impact quality of delivered electrical energy to the consumers, such as low voltage levels.

The low voltage levels bring a multiplicity of additional problems into the grid such as longer time required to deliver demanded electrical energy to the end users (intermittence or latencies). This will increase loads [A] in DNG, and with $[A]^2$ increased power loss as well. Besides increased power losses and longer time to deliver required energy, in the case that there is more energy demand at the same time per one phase, poor impedance in the DNG line could cause a drastic voltage drop, causing the entire system to shut-down.

To analyze and establish STABILITY within DNG, and balance between phases, parameter "k" that represent load constant is introduced. Value of perimeter "k" defines few cases:

- k = m =1 – at any loads for direct connection.
- k = m = 1.06 – for balanced loads connected through autotransformers.
- k = m = 1.1 – for unbalanced loads connected through autotransformers.
- k = √3 x m = 1.04 – for balanced loads connected through MVROT.
- k = m = 0.6 – for unbalanced loads connected through MVROT.

With parameters "k" and "m" defined it is possible to analyze and establish if the designed DNG is STABLE or not. Calculations are completed assuming that the designed DNG voltage drop per phase within SECTION 1, under maximal loads is ΔUd1=200[V], and in SECTION 2 is ΔUd2=40[V] and with introduction of another parameter "f", defining voltage drop in SECTION 1, that is dependent on load balance.

Table 1

voltage drop	balanced, CB1,CB2,CB3 closed							voltage drop ΔUd2 [V] = 40
Δd1 [V] = 200	m	k	f	Inv [A]	ΔUv [V]	Uv [V] = Un [V] - ΔUf [V]	Us [V] = m x Uv [V]	Up [V] = Us [V] - ΔUd2 [V]
direct connection	1	1	1	0.0	200	2400 [V] - 200 [V] = 2200	2200	2160.0
autotransformer	1.06	1.06	1	0.0	212	2400 [V] - 212 [V] = 2188	2319.28	2279.28
MVROT-250	0.6	1.04	2	0.0	208	4160 [V] - 416 [V] = 3744	2246.4	2206.41

In Table 1 with balanced loads and direct connection, calculations show that voltage levels at Step Down Transformers ("SDT") Up[V] (Figure 3) is within standards and drop is equal to 10% from nominal voltage. With autotransformer and MVROT connections we can see an increase of the loads per phase for 6% and 4% respectively. With loads $[A]^2$ there is an increase in power losses, but since the voltage level at SDT is higher by 5% with autotransformer connection and 2% with MVROT connection in comparison with direct connection, time of energy delivered will be shorter ($t[h]=Wg[Wh]/(Up[V])^2$), so energy losses are insignificant. See Figure 3.
Reviewing these calculated values in Table 1, with balanced loads and loss analyses shows that this DNG system is STABLE and optimal in all three cases.

As in a real situation and time DNG does not operate on ideal balanced loads, therefore a final conclusion can only be made if results are the same or better as for the same system under unbalanced loads.

Table 2

voltage drop	unbalanced, CB1-closed, CB2 i CB3 open							voltage drop ΔUd2 [V] = 80
ΔUd1 [V] = 200	m	k	f	Inv [A]	ΔUv [V]	Uv [V] = Un [V] - ΔUf [V]	Us [V] = m x Uv [V]	Up [V] = Us [V] - ΔUd2 [V]
direct connection	1	1	2	k x Ip[A]	200	2400 [V] - 400 [V] = 2000	2000	1920
autotransformer	1.1	1.1	2	k x Ip[A]	220	2400 [V] - 440 [V] = 1960	2156	2076
MVROT-250	0.6	0.6	2	0.0	120	4160 [V] - 240 [V] = 3920	2352.0	2272

Calculated results are shown in Table 2, for the unbalanced loads in the same DNG system under the same conditions as for the balanced loads, based that assumed voltage drop per phase within SECTION 1, under maximal loads, is ΔUd1=200[V], and in SECTION 2, is ΔUd2=80[V], (two times higher than under balanced loads, as currents circuit is closed through the single phase and neutral wire all the way to the main S/S), and introduction of the same parameter "f" that defines voltage drop in SECTION 1, dependent on load balance.

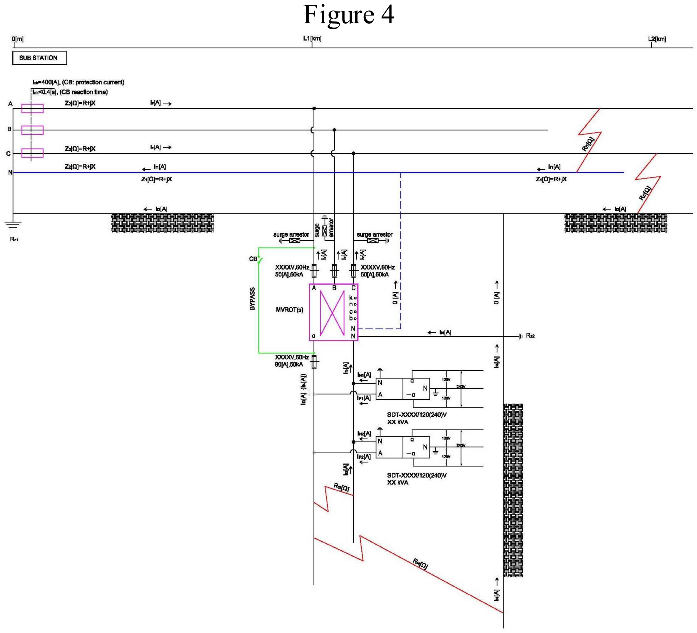
Under unbalanced loads the currents [A], (k * Ipt), within SECTION 1 are much smaller when connection between two sections is done through MVROT than directly or using autotransformers. At the same time power losses are directly related to $[A]^2$ which results in significant reduction of the power losses in comparison with direct and autotransformer connections.

From the voltage quality at the end of the SECTION 2 (see Table 2) the voltage levels Up[V] for direct and autotransformer connection is much lower than what standard allows (2160[V]=2400[V]*0.9) for this voltage level example, and the same voltage levels with MVROT connection is significantly higher and within standards.

Comparing the results between Table 1 and Table 2 concludes that the DNG system is STABLE only when connection between SECTION 1 and SECTION 2 is accomplished using MVROT technology, since only MVROT connection in both cases satisfies voltage level standards giving power quality to all users.

5. EXTRA PROTECTION AND GRID SELECTIVITY

Figure 4



Faults that could happen in a main three phase grid between Substation and MVROT or further up in that grid passing MVROT branch connection, will be eliminated by the existing protection in S/S, the same as with the original design. Faults that could happen in the branch, connected through MVROT (MVROT secondary side), will be eliminated by protection on MVROT. This is the extra protection to the main grid as only the branch with MVROT would see that fault which will be stopped at MVROT location. Since MVROT provide better (higher) voltage (U) and smaller line impendence (Zf), passing fault current (If) and its protection reaction time is improved (faster). (If = U/Zf)

This way grid protection selection is introduced since fuse protection at MVROT will react much faster and fault currents will newer reach the S/S protection. Faults behind MVROT (outages) will be localized to that branch only.

No currents are transferred into the neutral line from MVROT connection at primary side of MVROT and connecting neutral from the main grid to the MVROT improves grounding of MVROT, since complete system with all grounding becomes parallel connection of all grounding resistances. Gn.Res = (Rz1*Rz2)/(Rz1+Rz2). (See Figure 4)

Figure 4 shows possible fault scenarios in the grid. At the primary side of MVROT Faults 1 and 2 will see fault current [A] going to the main substation where S/S protection will react as per the original design without MVROT. For faults 3 and 4, protection at MVROT will react first as the fault current is high in neutral or in the ground.

Beside that Figure 4 is showing bypass in case MVROT needs to be replaced. MVROT is constructed so that it is easy to replace just main epoxy casted windings, saving magnetic core of the unit.

6. EFFICIENCIES AND AUTOMATIZATION

Up until now three phase systems with a neutral line and single-phase branches or singular loads tapped into individual phases will always have unbalanced loads. With that, current [A] will be present in neutral wire. That current is pure loss and unbalanced loads per phase can cause main transformers in substation to work under higher stress than what they have been design to. Secondly many existing grids do not have automatization and control capabilities and are inefficient.

With higher unbalanced loads there are higher losses. MVROT balances loads within the phases. For example, without MVROT in unbalanced system current in one phase would be (80A) and in neutral (80A) all the way to the main S/S. With MVROT, the same unbalanced load is divided between two phases so current in one phase is 46.32A and in second one is 46.32A delivering the same power. The neutral will have no currents from this load and is just passive line at that time.

Balancing these loads, currents [A] in phases become much smaller and with smaller currents $[A]^2$ power losses are reduced as well.

Integral parts built within the MVROT are Control PT, Metering PT and Metering CT. MVROT is capable of providing auxiliary power and reference / sensing parameters. (It has capacity to monitor power perimeters and through the remote transferring units, using any protocol, can send signals to SCADA system or voltage regulators in main substation).
Metering energy directly is possible as well with additional meter connected to MVROT control box.

Example of MVROT-250 Technical Data:

Height [mm]	940
Depth [mm]	460
Weight [kg]	870
Mechanical Protection	IP56/NEMA 3R
Ambient Temperature	-50 to +65
Primary Voltage [kV]	0.6 to 4.16
Secondary Voltage [kV]	0.11 to 2.5
Power: Sn [kVA]	up to 215
Power Factor: “COS fi”	0.97
Nominal Power [kVA]	185
Frequency [Hz]	50 / 60
BIL [kV]	30

Insulation Degree [kV]	7.2/20
Power Losses [kW]	Total 1% of Pnom
Harmonics	N/A (Does not generate / pass through)

Certified: CSA, IEC 60076-11 / 2004, EN 50160, NETA, C22.2 No. 47-13, IEEE C57.12.01 / 2015

Built in:	Metering PT	Control PT	Metering CT
Primary Voltage [kV]	4.16	4.16	4.16
Secondary Voltage [V]	120	120	-
Primary Current [A]	-	-	60
Secondary Current [A]	-	-	1 / 5
Class [%]	0.5%	3%	0.5%
Protection	3P	3P	-
Burden [VA]	100	300	10
BIL [kV]	30	30	30

- Other (higher) voltage levels are available as per specific requirements.

7. CONCLUSION

Traditional reconstruction methods for existing and inefficient distribution grids are expensive, time consuming, and some of them do not address all the problems that a grid can be exposed to. New grids cannot be designed to be perfectly balanced by using traditional methods.

The innovative technology shown in this paper will bring power quality into the existing grids with very fast installation, smaller investment and short term capital payback. Additionally, power providers will have more energy available to the existing or new consumers. Distribution grids become “selective” as extra protection will localize potential outages within small areas preventing big area blackouts.

Making existing grids stable, providing power quality per EN 50160, with all extreme cases under balanced and unbalanced loads that could happen in the grids is easily achievable with this technology. Balancing loads eliminates all currents in neutral line (and circuit current in ground) making the grid safer.

Having instrument transformers built in can make the entire grid SMART. By connecting a SCADA system with MVROT will provide significant benefits in automatization and optimization of the grids.

New distribution grids can be engineered using this technology to easily balance loads and with harmonics being eliminated / dissipated by MVROTs there will be no requirements for the big harmonic filters in main S/S.

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