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Reduction of CLPU Overload through Active Load Management

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SUMMARY

Cold Load Pick-Up (CLPU) is the increase in the feeder load after the distribution circuits are re-energized following extended outages. Load levels after an outage can be significantly higher than pre-outage levels, often exceeding the designed distribution feeder peak demand, and can persist for tens of minutes to hours. The extent and duration of cold load pick-up have a significant impact on the service restoration time. Utilities with high proportions of thermostatically controlled loads (such as electrical space and water heating, refrigeration and air conditioning) face a significant challenge of sharp load increase after service restoration, especially in regions where winter temperatures are extremely low (down to -40^{o} C), as it is the case in Québec, Canada. For such utilities, cold load pick-up is explicitly accounted for in planning and operation procedures; in fact, it is one of the top determining factors for high-to medium-voltage transformer sizing and overloading capabilities.
In this paper, the two different service restoration methodologies for the prevention of overload caused by the cold load pick-up are presented and compared. Both proposed approaches leverage remote control capabilities of the most advanced metering infrastructure already deployed and attempt to limit feeder overload and service restoration time by managing the post-outage customer re-connections and consumption. Results of the two algorithms are analyzed and compared against the full feeder restoration demonstrating the benefits of the approaches to the distribution system operator. For both algorithms, schedules are computed through the solution of a mixed-integer linear programming problem and results are presented for 15-minute time intervals.

KEYWORDS

Distribution network automation, service restoration, cold load pick-up, smart meters.

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1. Introduction

Service restoration (SR) is a procedure for restoring the power supply after a power outage. The primary objective of service restoration is to restore the electricity service to the interrupted customers after an outage while minimizing the restoration time. SR must be solved promptly to ensure customers' satisfaction [1]. In distribution networks with a high percentage of thermostatically controlled loads, utilities encounter the challenge of an increase in the load after restoration – Cold Load Pick-up (CLPU). Following an extended power outage, all homes which experienced the loss of power would require full power simultaneously, with no diversity in the load [2]. Following types of loads have a significant impact on CLPU duration and magnitude: water heating devices, space heating devices – throughout the winter, air-conditioning devices throughout the summer, refrigeration. The typical behaviour of the residential load with electrical heating after a one-hour outage is presented in Fig. 1. Load levels in utilities with high percentage of thermostatically controlled loads after an outage can be significantly higher than pre-outage levels, often exceeding the designed distribution feeder peak demand, and can persist for tens of minutes to hours [3]. Such behaviour causes thermal stress on the network equipment and may lead to further outages due to protection actions associated with sustained overcurrent operation during CLPU [4]. The significant impact on the CLPU peak and duration have outage duration and outdoor temperature. Therefore, the system must be designed so that it could be restored in the least possible time without causing any voltage violations, feeder overload or unacceptable transformer heating [5]. In network configurations where feeder cannot accommodate the increase in the load caused by cold load pick-up, the solution, presented in this work, is to employ an efficient service restoration strategy that will mitigate CLPU overload.

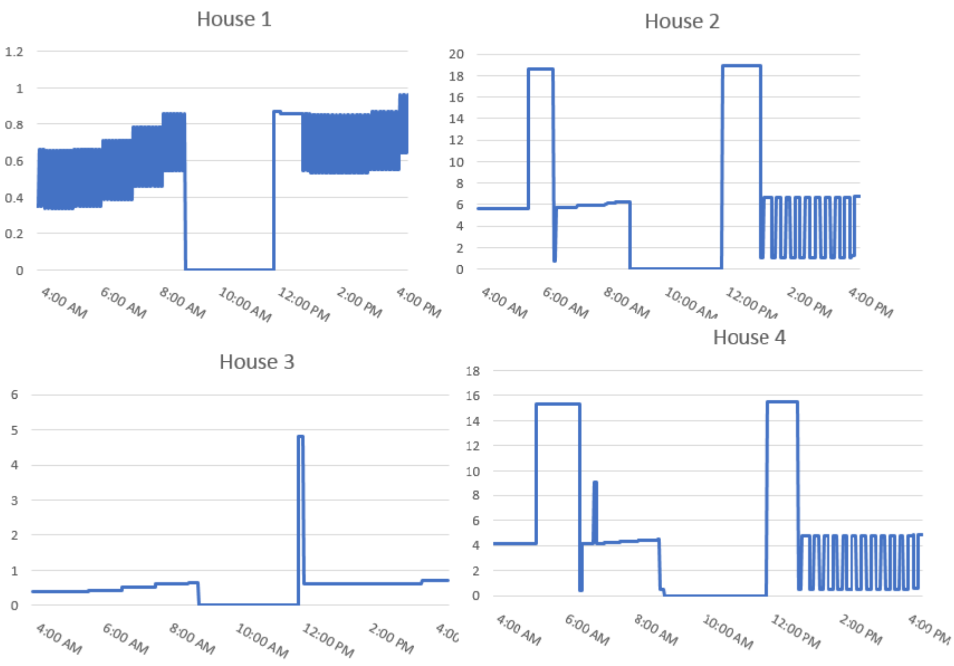

Fig. 1. Different CLPU responses after 1-hour outage

Current practices for service restoration rely on the load sharing among the feeders. When there is no available capacity on the adjacent feeder or when tie-switches are not available for control, these approaches cannot solve the problem of the overload caused by CLPU. Additionally, due to the potentially complex behaviour of the end-use loads, it is difficult to know in advance which portions of the distribution feeder should be connected at each step of a service restoration sequence to minimize CLPU [3]. Service restoration can be enhanced with load curtailment programs such as direct load control that allow system operators to directly and/or indirectly reduce a portion of total customer demand [6]. In recent work, it is investigated how demand response programs can be coordinated with distribution service restoration. Direct load control has been applied in [7], as a mean of support for the grid during emergency and contingency conditions, such as frequency regulation, phase balancing and cold load pick-up. Here it is suggested to restore the critical loads of the single customer while ramping non-critical load gradually to avoid overload after the restoration; however, the solution to this problem has not been given. The proposed approach in [6, 8] suggests load curtailment as a part of the restoration procedure; however, it is based on a ranking based heuristic search algorithm which makes it suitable for offline analysis but challenging to apply to real-time systems. Here is demonstrated that the load curtailment allows for a reduction of the total number of switch operations required, an increase to the number of customers served, and an increase to the total amount of load restored.

This paper proposes an alternative approach to service restoration problem that alleviates CLPU overload effects. To achieve this objective, two different algorithms that are based on active load management are proposed. The proposed approaches as an output provide the schedule for individual customer re-connection through the advanced metering infrastructure already deployed in distribution utilities. The SR scheduling problem is formulated as a Mixed Integer Linear Program (MILP) and it is applicable for real-time application and offline schedule generation. Case study results confirm the effectiveness of the developed methodology.

2. Service Restoration with Active Load Management

The proposed solution to the distribution feeder overload after the service restoration incorporates active load management as a part of the procedure. Once the outage has been cleared, load management can be applied in such a way to prevent overload by connecting the customers in the proposed sequence. A portion of the load is re-connected at every predefined time interval by sending the commands to the smart meters located at the service delivery points. The procedure ends once all customers are re-connected. The optimization problem is solved through the solution of mixed integer linear program. Service restoration algorithm as an input receives a network model and estimated cold load pick-up value and duration based on which generates customer re-connection schedule. The output of the optimization procedure is the schedule for customer re-connection at every predefined time interval. If the utility has the means to control the end use load/appliances directly, the level of partial re-connection is specified, and the service restoration procedure is enhanced with partial re-connection. Direct load control allows usage of the electricity to some extent to the partially supplied customers and, therefore, increases customer satisfaction.

Two approaches for service restoration with active load management are proposed depending on the distribution utility capabilities in terms of load control. The first approach incorporates scheduling full customer re-connection as a part of the restoration procedure, while the second one allows specifying the level of load curtailment at re-connection. Inputs to the optimization problem are:

- Distribution network data,
- Cold load pick-up model,
- Network asset operational limits.

The service restoration optimization problem is formulated as a minimization of the difference between the feeder load limit and the sum of the feeder consumption:

$$min \sum_{t=t_{start}}^{T_{restored}} \left[S_{max} - \sum_{i=1}^{N_{consumers}} [u(i,t) \cdot S_{cons}(i) \cdot p_{curve}(t,i) \cdot clpu(i,t)] \right] \quad (1)$$

$s.t.$

$$\sum_{i=1}^{N_{consumers}} u(i,t) \cdot S_{cons}(i) \cdot p_{curve}(t,i) \cdot clpu(i,t) \leq S_{max} \quad (2)$$

$$u(i,t) \geq u(i,t-1) \quad (3)$$

Where:

t – time at which calculation is done,

S_{max} – maximum allowed load,

$u(i,t)$ – ON/OFF status of i^{th} customer at time t for scheduled customer re connection approach or ON/PARTIAL_CONNECTION/OFF for approach with load curtailment,

$S_{cons}(i)$ – peak consumption of i^{th} customer,

$p_{curve}(t,i)$ – value from the load curve for the time t,

$clpu(i,t)$ – ratio between normal loading and loading after the outage of i^{th} customer at time t.

Flowchart diagram of the algorithm is presented in the Fig. 2.

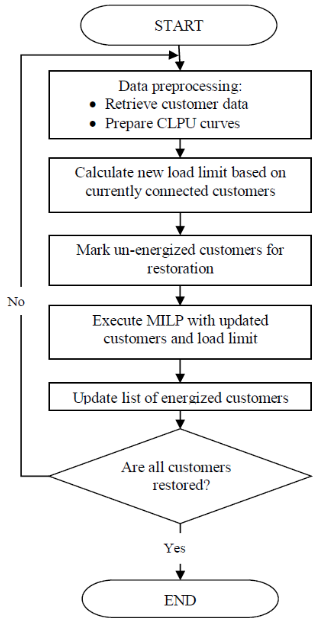

Fig. 2. Service restoration flowchart diagram

In the block *Calculate new load limit based on currently connected customers*, overload limit is calculated and updated in every iteration, based on connected customers in previous cycles and their current load (4):

$$S_{limit}(t) = S_{max} - \sum_{i=1}^{N_{consumers}} u(i,t) \cdot S_{cons}(i) \cdot clpu(i,t) \cdot p_{curve}(i,t) \tag{4}$$

Where:

t – time at which calculation is done,
$S_{limit}(t)$ – current calculated limit,
S_{max} – maximum allowed load,
$u(i,t)$ – ON/OFF status of i^{th} customer at time t for scheduled customer re-connection approach or ON/PARTIAL_CONNECTION/OFF for approach with load curtailment,
$S_{cons}(i)$ – peak consumption of i^{th} customer,
$p_{curve}(t,i)$ – value from the load curve for the time t,
$clpu(i,t)$ – ratio between normal loading and loading after the outage of i^{th} customer at time t.

Updated limit and list of customers not connected are at each cycle sent as an input to the MILP solver. MILP solver as an output gives newly connected customers. Load left to be restored for the current cycle is then calculated as shown in (5):

$$S_{notrestored}(t) = \sum_{i=1}^{N_{consumers}} z(i,t) \cdot clpu_{peak}(i) \cdot p_{curve}(i,t) \cdot S_{cons}(i) \tag{5}$$

Where:

$S_{notrestored}(t)$ – sum of the power not restored to the customers at time t,
t – time at which calculation is done,
$z(i,t)$ – complement of $u(i,t)$, has value 1 when $u(i,t)$=0 and opposite for customer re-connection algorithm and additionally for LC algorithm, 1- PARTIAL_CONNECTION when customer is connected partially.
$S_{cons}(i)$ – peak consumption of i^{th} customer,
$p_{curve}(t,i)$ – value from the load curve for the time t,
$clpu(i,t)$ – the ratio between normal loading and loading after the outage of i^{th} customer at time t.

Energy not supplied (ENS) is calculated as a sum of active power not restored for every time interval. Since the reactive power of the residential load can be neglected, ENS can be approximated with the amount of the load not restored on intervals:

$$ENS \approx \sum_{t=1}^{Tintervals} S_{notrestored}(t) \cdot \Delta t \quad (6)$$

Where:

ENS	–	energy not supplied during the restoration,
$S_{notrestored}(t)$	–	sum of the power not restored to the customers,
t	–	time at which calculation is done,
Δt	–	discrete time step.

Service restoration algorithms with partial and full customer re-connections using smart meters are verified against service restoration with full feeder re-connection. Verification shows benefits in terms of overload reduction. Cost is calculated in terms of energy not supplied due to the postponed reconnection of a customer.

Real time application consideration

The methodology proposed in this paper is applicable to both offline schedule generation and real-time operation. In offline mode, schedule for load restoration can be pre-calculated using historical data, and then applied in the restoration procedure. If the real-time load data is available from smart meters, this data can be used to feed the algorithm for each time interval, and re-connect customers based on the current load conditions. Application of customer re-connection methodology to a real distribution system requires at least the installation of smart meters with switching capabilities at end-use loads. However, smart meters have limitations in terms of the number of switching and operating voltage (for [9], which is a smart meter with two way communication of standard manufacturer, the specified operating voltage of 80% - 115% of the rated value with a switch of 10 000 operations). The partial customer re-connection would require additional investment to be able to perform load limitation at end-use load. Load limitations at the end-use load can be accomplished in several ways - installing the load control thermostats or direct load control switches at appliances that have the most significant impact on the cold load pick-up, such as heat pumps and water heaters, or with power meter limiters. With this level of customer control, there is a significant decrease in restoration time. However, such an infrastructure requires more substantial investments.

3. Simulation and Results

Verification of the proposed algorithms is done on the example of medium voltage distribution network feeder with 26 customers of different rated consumption. Cold load pick-up model used to model the increase in the load at re-connection is adopted from [10], and it is represented as a piecewise linear function with different parameters for different outdoor temperatures. Two different methodologies for the overload prevention caused by the cold load pick-up are presented and compared. Data preprocessing and post-processing is done in MATLAB, while optimization is done using Mixed Integer Linear Programming (MILP) solver in GAMS. The method as an input receives the rated consumption per customer, daily load curve and simplified CLPU model. The first algorithm proposes re-connection of the customer to the grid when its connection would not violate operation limits. Compared to the first algorithm, the second algorithm implements additional functionality - partial customer re-connection - Load Curtailment (LC). For the second algorithm, results are presented for limiting consumption to 70% of the total anticipated customer load at the first attempt of the re-connection. The results are presented for two different outdoor temperatures: $0°\mathrm{C}$ and $-40°\mathrm{C}$. Results for two cases are presented with three different graphs:

- Demand against time,
- Number of customers restored per time interval,
- Load not restored per time interval.

The plot of the *Demand against the time* shows a comparison between the demand for full feeder restoration and two of proposed SR algorithms. The trend shows the demand from the moment when an outage is cleared until the moment when the effect of CLPU vanishes. The graphs of *Number of* *customers restored per time interval* show the trend of customer re-connection; for service restoration with LC, it shows the portion of the customers partly connected and the time when all of the customers are fully re-supplied. The plot of *Load not restored* shows the calculated amount of the load left to be restored by two proposed algorithms, with and without load curtailment, for every time interval. This value is calculated using Equation 6. Loading limit of the feeder is in the chart represented as one p.u. and it is displayed as *Maximum Load*.

Results for **0**℃ *outdoor temperature*

For 0℃ outdoor temperature, at restoration started at 5 PM which are usually high loading conditions, anticipated load at the re-connection using full feeder restoration approach is three times larger than allowed (Fig. 3). For service restoration without load curtailment, restoration is completed four hours later due to the large customer which cannot be connected until the total load on the feeder decreases. Introducing load curtailment improves service restoration in terms of restoration time, and all customers are restored 2 hours earlier.

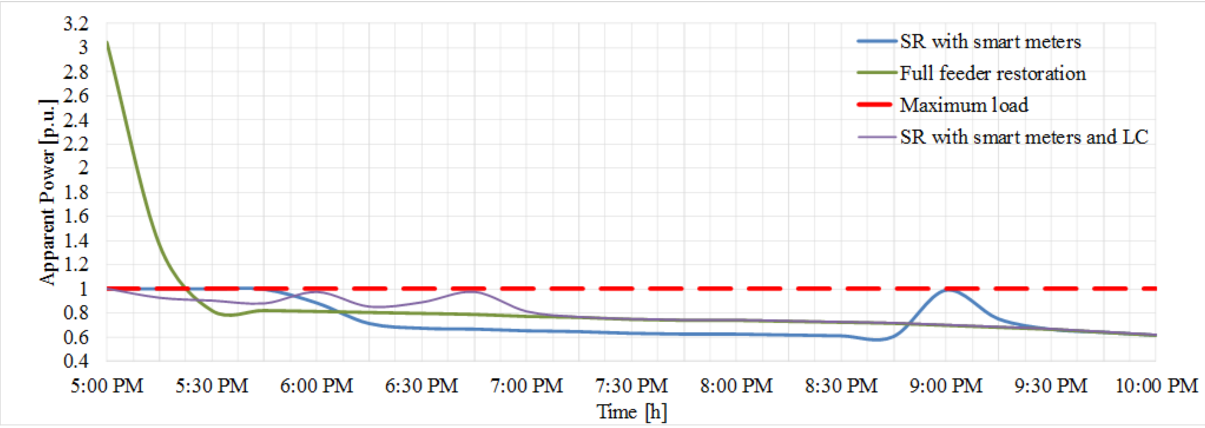

Fig. 3. Comparison of restoration for heavy load, 0℃ and 1-hour outage

Fig. 4 shows that by applying SR without load curtailment, the large load has remained disconnected for an extended period (five hours, including the outage). However, the majority of customers have been connected, and therefore, this represents the trade-off between the load connected compared to the violation of overload constraints. By applying direct load control through load curtailment, all customers are connected partially in an hour after the restoration has started, and entirely in 45 minutes after.

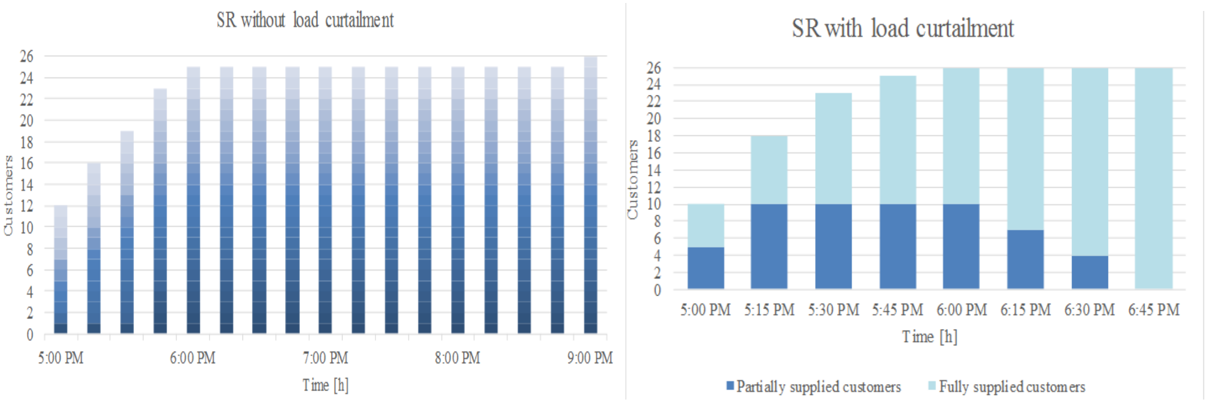

Fig. 4. Restored customers per time interval for SR without (left) and with (right) LC

In Fig. 4, left, it is shown that 25 out of 26 customers are restored in the first hour after the outage has been cleared, while the last one is restored at 9:15 PM. At the same figure on the right, all 26 customers are connected in an hour, while some of them only partially. In the following half an hour, all 26 customers are connected entirely. Fig. 5 shows load left to be restored for two algorithms, calculated using (5).

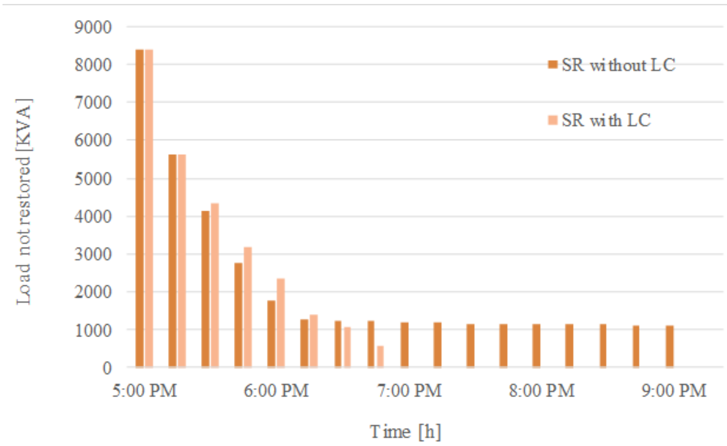

Fig. 5. Load not restored for SR with and without LC

Total Energy not supplied calculated as a sum for every time interval during the execution of two proposed service restoration procedures is approximately:

$$ENS \approx 7100\ kWh$$

$$ENS_{LC} \approx 4600\ kWh$$

Observing these two values, it can be concluded that the impact on the customers is significantly less by applying the load curtailment since the energy not supplied over restoration time is twice less than with simple customer re-connection.

Results for $-\mathbf{40}$℃ *outdoor temperature*

For -40℃ outdoor temperature, CLPU magnitude of the load is lower while the CLPU peak duration is extended comparing to 0℃. The magnitude is 2.1 p.u. of the allowed load at the time of re-connection, while the CLPU duration exceeds 1 hour. Fig. 6 shows the results of the optimization procedure for heavy loading conditions when the interruption duration is 3 hours. The peak value of the load after full feeder restoration is 1.7 p.u.

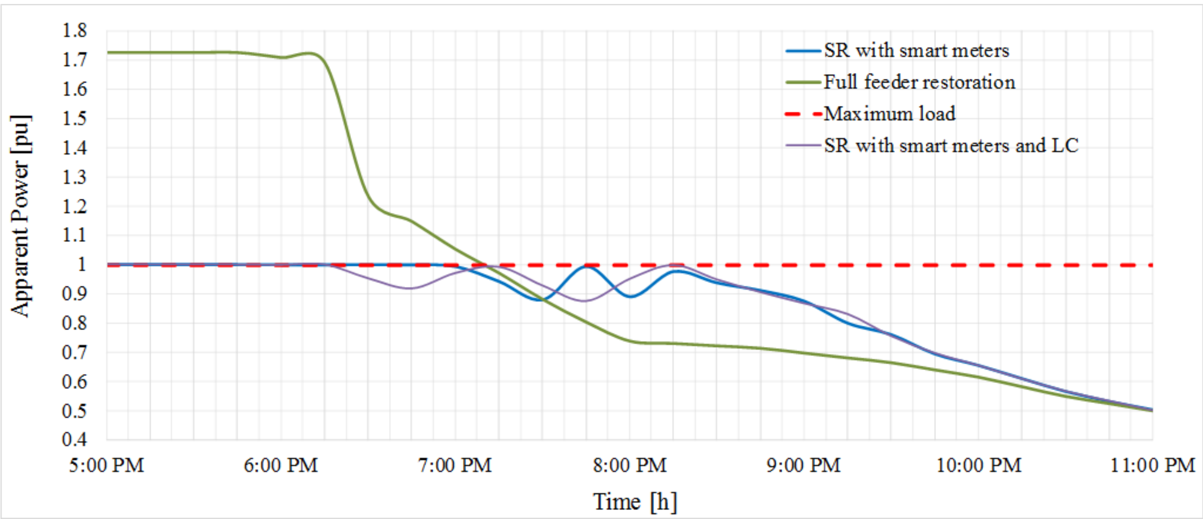

Fig. 6. Comparison of restoration for heavy load, $-\mathbf{40}$℃ and 3-hour outage

With full feeder restoration, the peak will be constant for longer than an hour. Since the peak of the power is twice as the overload limit, it is essential to reduce it by applying the proposed service restoration procedure. Having an overload like the one presented in Fig. 6 would trigger relay protection and potentially damage the equipment. Trends of connected customers are presented in Fig. 7. There is a slight improvement in the number of customers restored using load curtailment approach compared to the approach without LC.

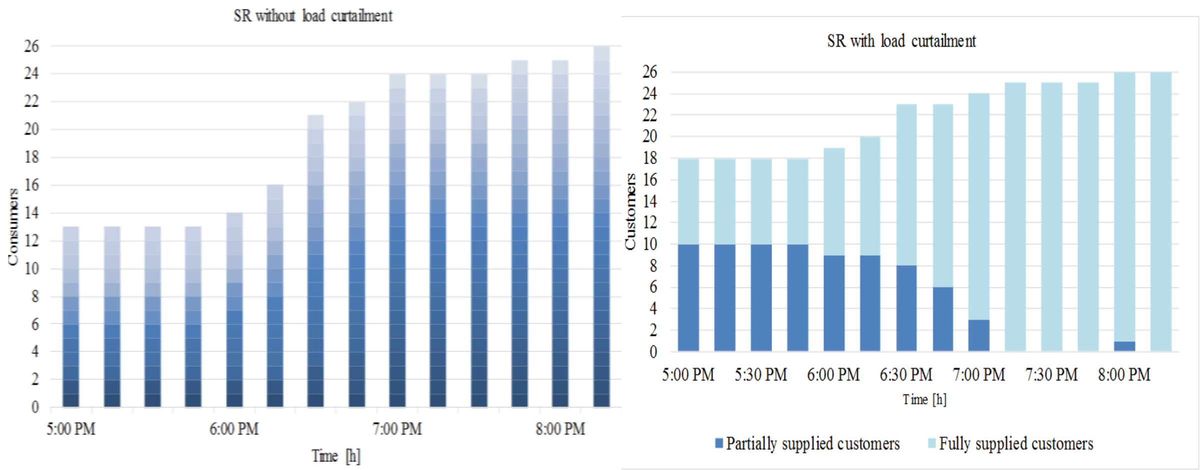

Fig. 7. Restored customers per time interval for SR without (left) and with (right) LC

Fig. 8. shows the trend of the load left to be restored for each time interval. The amount of the load after the first cycle remains constant until the CLPU effect starts to diminish.

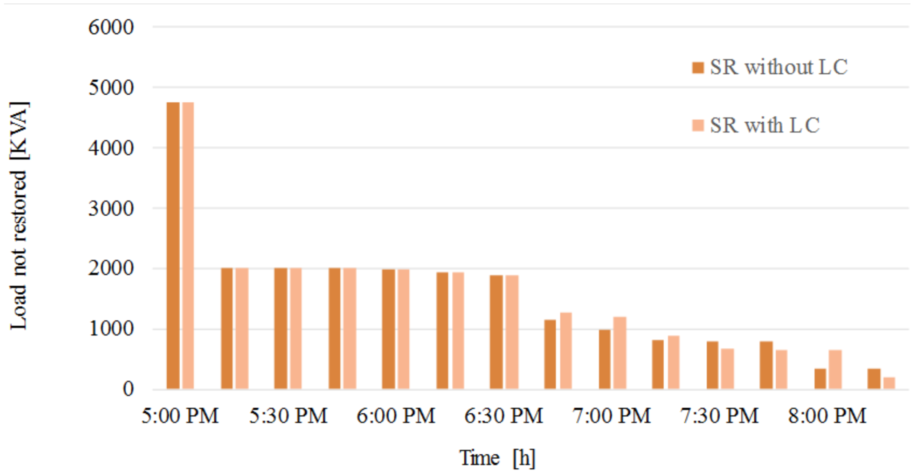

Fig. 8. Load not restored for SR with and without LC

Value of energy not supplied is approximately:

$$ENS \approx 4200\ kWh$$

$$ENS_{LC} \approx 4300\ kWh$$

From the values of energy not supplied, it can be observed that there is no significant improvement using load curtailment for restoration where CLPU peak has extended duration, which can also be seen with the number of customers restored per time interval.

4. Conclusion

In this paper, service restoration with active load management has been proposed and developed. Customers are re-connected entirely or partially depending on the distribution utility automation level using results of mixed integer linear program. Results of the algorithms are compared with the full feeder restoration presenting the benefits to the distribution system operator. Proposed service restoration gives an optimal schedule for customer re-connection through the solution of mixed integer linear program, with the aim to reduce overload that is a consequence of cold load pick-up. From the presented results, it can be concluded that CLPU overload can be successfully mitigated without violating overload constraints. The restoration is faster if distribution utility has a possibility for direct load control. The potential issue of this approach is that the customer re-connection will be randomly delayed. Delay is significantly reduced if load curtailment is applied. The advantages of the proposed approach are savings that can be calculated as postponed investments for a network upgrade. Service restoration with active load management can contribute to delaying network reinforcements or reduce the necessary ratings of new distribution circuits, which could result in considerable savings for utility.

BIBLIOGRAPHY

[1] L. T. Marques, A. C. B. Delbem, and J. B. A. London, "Service Restoration With Prioritization of Customers and Switches and Determination of Switching Sequence," *IEEE Transactions on Smart Grid,* vol. 9, no. 3, pp. 2359-2370, 2018.

[2] E. Agneholm and J. Daalder, "Cold load pick-up of residential load," *IEE Proceedings - Generation, Transmission and Distribution,* vol. 147, no. 1, pp. 44-50, 2000.

[3] K. P. Schneider, E. Sortomme, S. S. Venkata, M. T. Miller, and L. Ponder, "Evaluating the magnitude and duration of cold load pick-up on residential distribution feeders using multi-state load models," *IEEE Transactions on Power Systems,* https://doi.org/10.1109/TPWRS.2015.2494882 vol. 31, no. 5, pp. 3765-3774, 2016.

[4] F. Friend, "Cold load pickup issues," in *2009 62nd Annual Conference for Protective Relay Engineers*, 2009, pp. 176-187.

[5] V. Gupta and A. Pahwa, "A voltage drop-based approach to include cold load pickup in design of distribution systems," *IEEE Transactions on Power Systems,* vol. 19, no. 2, pp. 957-963, 2004.

[6] M. R. Kleinberg, K. Miu, and H. Chiang, "Improving Service Restoration of Power Distribution Systems Through Load Curtailment of In-Service Customers," *IEEE Transactions on Power Systems,* vol. 26, no. 3, pp. 1110-1117, 2011.

[7] H. Johal, K. Anaparthi, and J. Black, "Demand response as a strategy to support grid operation in different time scales," in *2012 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2012, pp. 1461-1467.

[8] M. Kleinberg, K. Miu, and H. Chiang, "Service restoration of power distribution systems incorporating load curtailment," in *2009 IEEE International Symposium on Circuits and Systems*, 2009, pp. 1709-1712.

[9] Landis+Gyr. *Electricity meter FOCUS AX*, 011808-06, 2014.

[10] S. Lefebvre and C. Desbiens, "Residential load modeling for predicting distribution transformer load behavior, feeder load and cold load pickup," *International Journal of Electrical Power & Energy Systems,* vol. 24, no. 4, pp. 285-293, 2002/05/01/ 2002.