Utilization Improvement of Transformers Using Demand Response

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***Abstract*—Due to load growth, aging infrastructure, and a competitive environment, innovative solutions are required by electrical utilities to enhance the utilization of transformers which are cost intensive. This paper proposes a demand response optimization model based on transformer hottest-spot temperature. The optimization model quantifies the improvement of transformer utilization through DR. The proposed model is applied to a typical Finnish residential primary and secondary distribution transformers for case studies of load with and without DR. The results show that the loading on the transformers can be significantly increased without sacrificing the life of transformers. The gain in utilization depends on the DR capability of the load. Significant monetary benefits can be achieved with the deployment of the proposed model in a real system.**

***Index Terms*—Aging, asset utilization, demand response, loss of life, power distribution, smart grid, transformer.**

I. Introduction

TRANSFORMERS are generally the most expensive asset in a distribution system [1]. Their high utilization efficiency is important in order to receive rational return on investments [2]. Because of low load factor and contingency requirements, the utilization efficiency of transformers is ordinary. They traditionally operate at 40%–60% loading during normal conditions [1]. As stated in [3], approximately 25% of distribution assets are used only for 440 h of peak load in the U.S. Moreover, owing to load growth at peak hours and an aging infrastructure, upgrading transformers is required at substations. The classical approach of reinforcement is expensive [4]. Therefore, electric utilities are in search of innovative methods to increase asset utilization [2].

Continuous monitoring and loading equipment up to their dynamic thermal rating (DTR) is a method of increasing the use of assets [5]–[7]. Demand response (DR), a technique for decreasing load in smart grid, is another way to improve the utilization of equipment by reducing peak demand. However, the use of DTR or DR alone cannot provide the ample potential benefit toward utilization improvement. In case of DTR, peak load hours still limit the loading of equipment whereas for DR, static rating is the limiting factor which does not ensure best asset utilization because the static ratings are based on the worst case weather and load conditions. The combination of DR and DTR can provide substantial gain in asset utilization efficiency.

The dynamic thermal ratings of transformers have been studied well [8], [9]. IEEE standard [8] suggests a maximum hottest-spot temperature (HST) of 110 °C for continuous operation and 200 °C for short duration during contingencies. The operation above an HST of 140 °C is recommended only after consultation with the manufacturer since it may produce gassing in solid insulation and oil, leading to dielectric strength weakness.

In recent literature, the effect of DR has been investigated on transformers. Most of the studies focused on the integration of additional load of electrical vehicles in the network without an adverse influence on the life of transformers. The controlled and uncontrolled electric vehicles (EVs) charging impact on a secondary distribution transformer (medium-voltage/low-voltage) was assessed by several researchers [10]–[13]. In [14], the problem of additional load of EV charging was solved by the DR of flexible household appliances. The DR was used to limit the demand to a certain level; however, DTR was not considered. The effect of DR on the lifetime of a secondary distribution transformer was assessed by optimizing the transformer temperature in [15]. The thermal dynamics were considered in that study; however, the optimization objective of reducing the sum of HST over a day by DR is not effective because load shifting can only change the average hottest temperature if changes in ambient temperature are considerable. Furthermore, the utilization increase of a transformer was not evaluated in [15]. In [10]–[15], typical U.S. secondary distribution transformers supplying power to a small number of houses were considered. However, this paper deals with a typical European system consisting of large secondary distribution transformers (1.6 MVA) serving a large amount of customers.

In this paper, we study the potential of DR in increasing the utilization of transformers for a typical Finnish residential area. A dynamic thermal model was used for the prediction of HST and insulation aging. One year of automatic meter reading (AMR) hourly measured residential electric power load data and one year of ambient temperature data were integrated into the model for realistic simulation. The transformer hottest-spot-limit-based optimization model was developed to find optimal DR activation. The impact of DR was studied for

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the power transformer and secondary distribution transformers that supply power to various heating-type households, in the network considered.

The results indicate that the transformers' utilization can be increased considerably by using DR. This improvement in utilization is without sacrificing the age of the transformers significantly. The magnitude of the utilization benefit depends on the DR capability of the load. The loading increase can provide monetary benefits by delaying the investments.

This paper is organized as follows: Section II presents the preliminary basics. An algorithm comprising an optimization model is proposed in Section III. Section IV provides the details of the test system. Case studies and results are described in Section V. The conclusions follow in Section VI.

II. Preliminary Basics

The transformer thermal model for calculating HST, aging equations, and DR basics is described in this section.

A. Transformer HST

The transformer winding HST (θ_H) can be estimated by (1) [8]. It consists of three components: 1) ambient temperature (θ_A); 2) top-oil rise over ambient temperature ($\Delta\theta_{TO}$); and 3) winding hottest-spot rise over top-oil temperature ($\Delta\theta_H$). All of the temperatures are in °C.

$$\theta_H = \theta_A + \Delta\theta_{TO} + \Delta\theta_H. \tag{1}$$

The top-oil rise and HST rise are given by the following:

$$\Delta\theta_{TO} = (\Delta\theta_{TO,U} - \Delta\theta_{TO,i})(1 - \exp^{-t/\tau_{TO}}) + \Delta\theta_{TO,i} \tag{2}$$
$$\Delta\theta_H = (\Delta\theta_{H,U} - \Delta\theta_{H,i})(1 - \exp^{-t/\tau_w}) + \Delta\theta_{H,i} \tag{3}$$

where $\Delta\theta_{TO,U}$ and $\Delta\theta_{TO,i}$ are ultimate and initial top-oil rise over ambient temperature, τ_{TO} is oil time constant, $\Delta\theta_{H,U}$ and $\Delta\theta_{H,i}$ are ultimate and initial hottest-spot rise over top-oil temperature, and τ_w is the winding time constant.

The ultimate top-oil rise and ultimate hottest-spot rise can be calculated by the following formula:

$$\Delta\theta_{TO,U} = \Delta\theta_{TO,R}\left[\frac{(K_U^2 R + 1)}{(R+1)}\right]^n \tag{4}$$
$$\Delta\theta_{H,U} = \Delta\theta_{H,R} K_U^{2m} \tag{5}$$

where $\Delta\theta_{TO,R}$, $\Delta\theta_{H,R}$ are top-oil rise and hottest-spot at rated load; K_U is the ratio of ultimate to rated load; R is the load loss ratio; and m and n are factors that depend on the type of cooling of the transformer.

B. Transformer Aging

Equation (6) describes the formula for calculating the aging acceleration factor (F_{AA}) of thermally upgraded paper (reference temperature 110 °C) [8]. The F_{AA} of a transformer is an exponential function of winding HST (θ_H)

$$F_{AA} = \exp\left(\frac{15000}{383} - \frac{15000}{\theta_H + 273}\right). \tag{6}$$

The equivalent aging factor (F_{EQA}) for the total time period can be calculated by (7) as in [8], where r is the index of time interval Δt, N is the total number of time intervals, and $F_{AA,r}$ is the aging acceleration factor for Δt_r. The transformer continuous 24-h operation with an HST of 110 °C yields an equivalent aging factor of unity

$$F_{\mathrm{EQA}} = \frac{\sum_{r=1}^{N} F_{AA,r}\Delta t_r}{\sum_{r=1}^{N} \Delta t_r}. \tag{7}$$

The percent loss of life (LOL) of the transformer for t hours of operation can be calculated by (8). Normal insulation life of the transformer is 180 000 hours (20.55 yr), with continuous operation at the HST of 110 °C [8]

$$\%\,\mathrm{LOL} = \frac{F_{\mathrm{EQA}} \times t \times 100}{\text{Normal insulation life}}. \tag{8}$$

C. Demand Response

DR refers to the "changes in electricity usage by the end-use customers from their normal consumption pattern in response to changes in the price of electricity over time or when system reliability is jeopardized" [16]. Three major strategies of DR are: shifting (changing time of use of load), foregoing (reducing load without making up the load later), and onsite generation [16]. In this paper, load shifting is considered as the applicable strategy.

Domestic appliances can be classified into different categories: heating, ventilation, and air conditioning (HVAC), cold appliances (refrigerator and freezer), wet appliances (washing machine, clothes dryer, and dish washers), lighting, cooking loads, brown appliances (video and audio devices), and miscellaneous appliances [17]. From the DR aspect, the household end-use appliances can be divided into two groups: 1) flexible and 2) critical. Flexible appliances can be displaced in time whereas critical appliances do not offer such elasticity in operation. We have considered HVAC, cold appliances, and wet appliances as flexible loads. All other appliances are considered critical. The DR capability of household appliances is listed in Table I [18]–[20].

TABLE I
Demand Response Potential of Domestic Appliances.[18]–[20]

Appliance		DR Potential (Hours)
Washing Machine		4
Clothes Dryer		1
Dish Washer		5
Water Heater	Storage	3
	Direct	-
Refrigerator / Freezer		1
Air Conditioner		1
Space Heating	Storage	5
	Direct	1

The wet appliances can provide DR by delaying wash and dry operation, modifying cycle time, or by using cold water instead of hot water. The cold appliances offer flexibility by delaying defrost and ice making operation, modifying run time, reduced feature operation, and by temperature shift. Air conditioners and

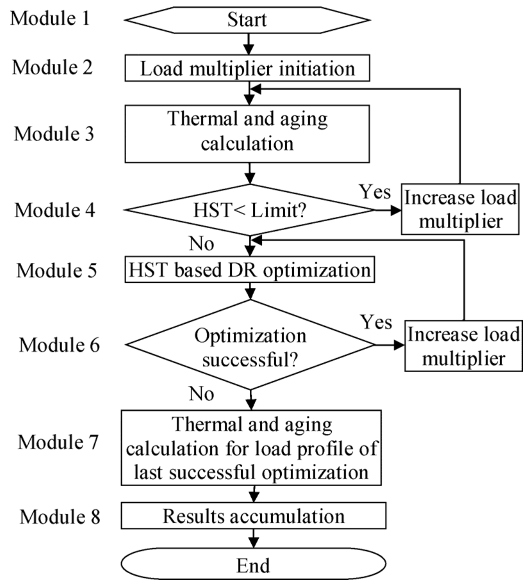

Fig. 1. Flow diagram of the proposed algorithm.

heaters enable the DR feature by delaying operation for a certain time and by slightly changing the setpoint temperature for required duration. Storage heaters offer higher flexibility compared to direct heaters.

III. Proposed Algorithm

Fig. 1 shows the flow diagram of the algorithm for calculating the required increase in transformer utilization with DR-enabled loads. This diagram contains the following eight modules.

- Module 1: The data related to the system are obtained in this block. The data may include transformer input parameters for thermal calculations, annual load profile, DR capability of load, ambient temperature, and HST limit.
- Module 2: Load multiplier is initialized here. Load multiplier refers to the scaling of the basic load profile. It is incremented step by step to find loading limits.
- Module 3: In this module, the new load profile is obtained by multiplication of load multiplier and initial load data. Then, thermal and aging values are calculated for an annual load profile using (1)–(8).
- Module 4: The HST of the transformer from module three is compared with the maximum-allowed value. If it is less than a set limit, then the load multiplier is incremented. This process is repeated until the HST limit is reached. This module provides the value of maximum loading for transformer operation within an HST limit without DR.
- Module 5: The HST of the transformer exceeded the allowed limit for last loading values in Module 4. Therefore, load reduction is required to operate the transformer within temperature limits. Load on the transformer is reduced by activation of DR. In this module, the optimization model is used to find the modified load profile.

The objective is to reduce the HST to the specific value by using a minimum amount of load shifting. The minimum use of load shifting is formulated by objective function (9), and the HST reduction to a certain limit is framed by constraint (10) of the optimization. In order to restrict the effect of a DR activity to only that day, the optimization is applied over 24-h duration

$$\text{Minimize } f = \sum_{t=1}^{24} \sum_{t'=1}^{T_{\text{DR}}^{\max}} L_{\text{DR}}^{t,t'} \tag{9}$$

where $L_{\text{DR}}^{t,t'}$ is the load deferred from time t to later time t' and $T_{\text{DR}}^{\max}$ is the maximum time for which a load can be deferred. The two summations cover the load postponed to all later times at each hour of the day.

The optimization function is subject to the following constraints:

- The HST at any time $t(\theta_{H,t})$ should be less than or equal to maximum-allowed HST $(\widehat{\theta_H})$

$$\theta_{H,t} \leq \widehat{\theta_H}. \tag{10}$$

  The HST on the left-hand side in (10) is calculated by (4) and (5), and by using the modified load profile (13).
- The sum of load that can be deferred to a particular later time (t_m) is limited to the sum of available power that can be deferred to that time or longer

$$\sum_{t'=t_m}^{T_{\text{DR}}^{\max}} L_{\text{DR}}^{t,t'} \leq \sum_{t'=t_m}^{T_{\text{DR}}^{\max}} P_{\text{DR}}^{t,t'} \tag{11}$$

  where $\forall t_m \in \{1, 2, 3, \ldots, T_{\text{DR}}^{\max}\}$, $t < t'$, and $P_{DR}^{t,t'}$ is the available power under the DR contract that can be deferred from time t to t'. This constraint ensures that the total demand postponement at a time is less than the overall DR capability of the load at that time.
- The amount of load transfer at any time can be between zero and DR capability of load at that time. This constraint sets the lower and upper bounds of load deferments between two particular times

$$0 \leq L_{\text{DR}}^{t,t'} \leq P_{\text{DR}}^{t,t'}. \tag{12}$$

  The total load at time t after DR activation (P_{tot}^t) is the summation of available flexible load (P_{DR}^t), critical load (P_C^t), and load that was deferred to t in prior times $(L_{DR}^{t',t})$ minus load deferred to later times $(L_{DR}^{t,t'})$

$$P_{\text{tot}}^t = P_{\text{DR}}^t + P_C^t + \sum_{t'=t-T_{\text{DR}}^{\max}}^{t-1} L_{\text{DR}}^{t',t} - \sum_{t'=1}^{T_{\text{DR}}^{\max}} L_{\text{DR}}^{t,t'}. \tag{13}$$

  The output of the optimization is the modified load profile (13) and DR actions $(L_{\text{DR}}^{t,t'})$ taken to reduce the HST to the definite level.

Equations (4) and (5) for HST contain the parameters m and n whose values depend on the type of cooling for the transformer. The values of these parameters are between 0.8 and 1 [8]. In case these parameters are not unity, then the optimization problem cannot be solved by a usual solver, such as CPLEX. To make the optimization problem solvable by usual solvers, these parameters are assumed to be unity [15].

- Module 6: In this module, the success or failure of optimization is determined. The success of optimization indicates that DR activation is able to reduce HST to the de-

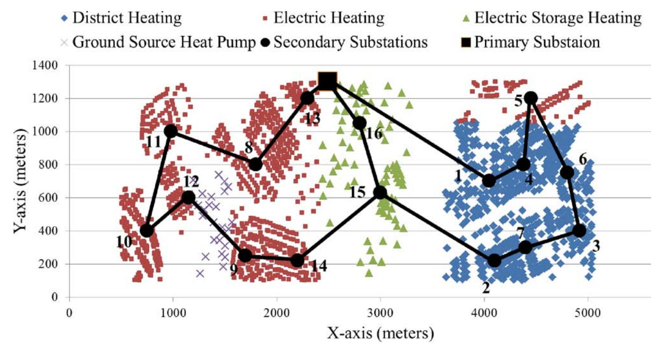

Fig. 2. Test system showing the distribution of household types and substations.

sired level. The load multiplier is incremented and module 5 and 6 are revisited. Since the aim of the algorithm is to determine the maximum potential utilization increase of the transformer, therefore, this loop is repeated until the optimization fails to reach a solution. The load multiplier in the last successful optimization gives the maximum possible loading of the transformer for set peak HST, taking into account the DR.

- Module 7: The thermal and aging values are computed for the final load profile obtained from Module 6.
- Module 8: Finally, the results of the previous modules are accumulated and stored.

In the presence of residential distributed generation (DG), the proposed algorithm will remain the same except that the output of the DG (P^t_{DG}) will be subtracted from the critical part of the load as long as the DG output is uncontrolled and modelled deterministically. Equation (13) for the modified load profile will be altered to the following expression:

$$P^t_{\text{tot}} = P^t_{\text{DR}} + P^t_C - P^t_{\text{DG}} + \sum_{t'=t-T^{\max}_{\text{DR}}}^{t-1} L^{t',t}_{\text{DR}} - \sum_{t'=1}^{T^{\max}_{\text{DR}}} L^{t,t'}_{\text{DR}}. \quad (14)$$

Since residential DG supplies the load directly, therefore, the net load on the transformer will decrease. Thus, the higher load growths can be supported by such a system. However, during situations of higher DG production than the demand, reverse power will flow through the transformer. In order to limit the load during the reverse flows, the optimization model will try to increase the demand at instances of higher DG output through load shifting via DR.

IV. Test System

A typical Finnish residential area distribution network, as shown in the schematic of Fig. 2, is considered to be a test system [21]. A primary substation transformer (40 MVA, 110/20 kV) supplies power to 16 secondary substation transformers (1.6 MVA, 20/0.4 kV). All of the transformers are installed outdoors. There are 1800 households in the system belonging to four primary heating-type groups; direct electric heating (DE), district heating (DIST), electric-storage heating (STORE), and ground-source heat pump (GSHP).

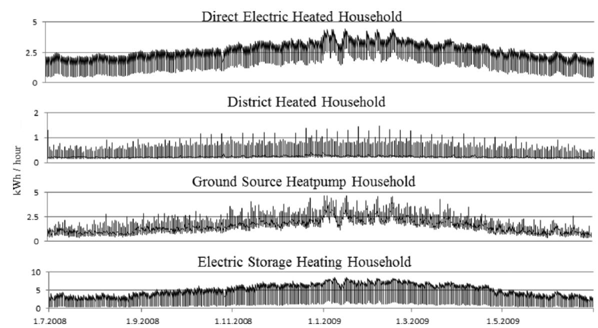

Fig. 3. Typical annual hourly load profile of household types.

TABLE II
Distribution of Households Types for Secondary Substations

SS#.	DE	DIST	GSHP	STORE	Cluster
1	151	6	0	0	C1
2	116	0	0	0	C1
3	85	0	0	0	C1
4	101	0	0	0	C1
5	20	75	0	0	C4
6	101	8	0	0	C1
7	99	0	0	0	C1
8	0	213	0	5	C2
9	0	126	0	26	C4
10	0	150	0	0	C2
11	0	84	0	0	C2
12	0	70	0	27	C4
13	0	105	3	0	C2
14	0	119	4	0	C2
15	0	0	56	0	C3
16	0	4	46	0	C3
Total	673	960	109	58	

TABLE III
Secondary Distribution Transformer Parameters

Type of cooling.	ONAN
Hottest-spot rise over ambient at rated load.	80°C
Top-oil rise over ambient at rated load.	55°C
Load loss at rated load to no-load loss.	8
Winding time constant.	5 min
Oil time constant.	155 min

The distinct load behavior of each type of household is shown in Fig. 3. All electric power consuming heating types have higher consumption and follow similar trends to ambient temperature in a year. Due to the charging and discharging behavior of electric-storage heaters, daily peak loadings are visible at certain hours of the day. Ground-source heat pumps show increased consumption in the very cold hours when the supportive direct electric heaters are switched on. These distinct behaviors have a cumulative effect on substation loading based on their count in a substation area.

The number and type of households under each secondary substation transformer are listed in Table II. Based on the number of each type of household in a secondary distribution substation area, transformers are grouped into four clusters: 1) C1; DE dominant area; 2) C2; DIST dominant area; 3) C3; GSHP dominant area; and 4) C4; area containing mix primary heating-type households. The one-year AMR hourly load data

TABLE IV
CASE STUDY RESULTS FOR THE PRIMARY SUBSTATION TRANSFORMER

Scenario	AverageLoad (p.u.)	Case 1 (without DR)			Case 2 (with DR)			Difference		
		Peak Load (p.u.)	HST max (°C)	LOL (%)	Peak Load (p.u.)	HST max (°C)	LOL (%)	Peak Load (p.u.)	HST max (°C)	LOL (%)
1	0.37	1.00	37	0.00003	1.00	37	0.00003	-	-	-
2	0.52	1.40	80	0.00036	1.40	80	0.00036	-	-	-
3	0.60	1.62	110	0.00494	1.62	110	0.00492	-	-	-
4	0.61	1.65	115	0.00726	1.60	110	0.00692	0.05	5	0.00034
5	0.69	1.85	146	0.10049	1.68	110	0.05063	0.17	36	0.04986
6	0.73	1.95	164	0.37484	1.66	110	0.10478	0.29	54	0.27006
7	0.74	1.98	169	0.55480	1.66	110	0.12780	0.32	59	0.42699
8	0.75	2.00	173	0.71984	1.70	113	0.18072	0.30	60	0.53912

for each type of household, measured in central Finland, is used to build the load profile of the transformers.

To determine the DR capability of the load, the first load profile is disaggregated to estimate end-use appliance power consumption. The load disaggregation is achieved by applying the conditional demand analysis technique to the one-year AMR measured data, statistical information gathered through questionnaire [22], and weather data. Then, average DR capacity of the load is determined by utilizing this information along with DR values of appliances from Table I.

The input data for thermal calculations of primary transformers are taken from [23] and data for secondary transformers are given in Table III. The quadratic optimization problem formulated in Section III is solved via the general algebraic modelling system (GAMS) [24] environment.

V. CASE STUDIES AND RESULTS

The analysis is conducted for all transformers in the network for the following two cases:

Case 1) In this base case, the load is firm.

Case 2) Functional DR is considered in this case.

The maximum HST limit of 110 °C is considered in both cases. The results for four substation transformers; primary, SS4, SS10, and SS15 are provided in detail. These selected transformers are representative of the cluster of transformers, grouped based on the heating type of the load. Eight suitable loading scenarios are selected to elaborate the results for each transformer. Scenario 1 is for the rated load, maximum DTR is shown by scenario 3, and scenario 2 is for the loading condition between scenarios 1 and 3. Scenarios 4 to 7 represent the progressive loading situation where DR is activated to limit HST. Scenario 7 denotes maximum possible loading with available DR at the load. In scenario 8, the HST limit is relaxed to 115 °C to evaluate the amount of winding HST that can be reduced by fully using the DR capability of load beyond scenario 7.

Table IV presents the results for the loading scenarios for the primary substation transformer. Per-unit values in the table are based on the transformer rating. Maximum HST observed by the transformer is 37 °C for the rated load in scenario# 1 and 80 °C for 140% loading in scenario# 2 of Case 1. These low HSTs are due to very low ambient temperatures in the winter when load peaks are observed. In scenario 3, HST (110 °C) is reached for peak loading of 162% in Case 1. DR is required to restrict HST for loading above this level.

TABLE V
ANNUAL LOAD TRANSFER UNDER DR IN CASE 2 FOR THE PRIMARY SUBSTATION TRANSFORMER

Scenario (Case 2)	Total demand shift under DR in a year (kWh)						
	1 h	2 h	3 h	4 h	5 h	Total	% of W_a
4	354	446	398	339	281	1 818	0.001
5	62 755	21 835	22 354	13 658	28 077	148 679	0.062
6	325 826	52 975	49 209	42 558	112 199	582 766	0.229
7	526 472	68 207	67 912	52 507	139 361	854 459	0.330

During scenario 4, HST reaches 115 °C (Case 1), which is reduced to 110 °C (Case 2) by optimally shifting the flexible demand. Similarly, for loading scenarios 5–7, the maximum HSTs are 146 °C, 164 °C, and 169 °C, respectively. In all of these scenarios, demand shifting is able to reduce HST to the set limit. For loading above 198%, the optimization solution does not exist because available DR is not enough to decrease HST to the desired value.

In Case 1 (without DR), the transformer can be loaded up to 162% (scenario 3) and the corresponding average load is 60%, given that HST remains within the specified value. However, in Case 2 (with DR), the average load of 74% can be supplied (scenario# 7) by the transformer without violating the set HST limit. The LOL of the transformer is also reduced in Case 2. However, the LOL is not significant in both cases due to low average load and ambient temperatures. The ambient temperature corresponding to maximum HST is around -14 °C.

Table V shows the annual demand shift required in obtaining the results of Case 2 in Table IV. The demand shift quantities are listed for one- to five-hour delay duration and as a percentage of annual demand (W_a). The decrease of 5 °C in maximum HST for scenario 4 is achieved by shifting 1818 kWh of flexible demand which is equivalent to 0.001% of annual demand. The demand delay requirement is high for higher reduction in HST. The maximum decrease in HST (59 °C) in scenario 7 is gained by shifting 854 MWh of load that is equal to 0.33% of annual demand. In this scenario, the major portion of demand shift is for one hour.

Fig. 4 presents the peak-day primary transformer loading and related temperatures of both cases for scenario 5. The total demand shift in the day to limit HST to 110 °C is 45.64 MWh. The demand deferment for 1, 2, 3, 4, and 5 h are 28.82, 2.56, 3.77, 3.86, and 6.63 MWh, respectively.

The results for the SS4 transformer (cluster C1) are presented in Table VI. In scenarios 1 through 3, the maximum HST limit is

TABLE VI
CASE STUDY RESULTS FOR THE SS4 TRANSFORMER

Scenario	AverageLoad (p.u.)	Case 1 (without DR)			Case 2 (with DR)			Difference		
		Peak Load (p.u.)	HST max (°C)	LOL (%)	Peak Load (p.u.)	HST max (°C)	LOL (%)	Peak Load (p.u.)	HST max (°C)	LOL (%)
1	0.32	1.00	45	0.00003	1.00	45	0.00003	-	-	-
2	0.40	1.25	76	0.00025	1.25	76	0.00025	-	-	-
3	0.47	1.48	110	0.00576	1.48	110	0.00568	-	-	-
4	0.48	1.50	115	0.00776	1.48	110	0.00729	0.02	5	0.00047
5	0.53	1.65	141	0.07434	1.54	110	0.03166	0.11	31	0.04268
6	0.56	1.75	160	0.33399	1.54	110	0.06820	0.21	50	0.26579
7	0.61	1.92	195	4.02537	1.54	110	0.21831	0.38	85	3.80706
8	0.62	1.94	199	5.35525	1.57	114	0.31449	0.37	85	5.04076

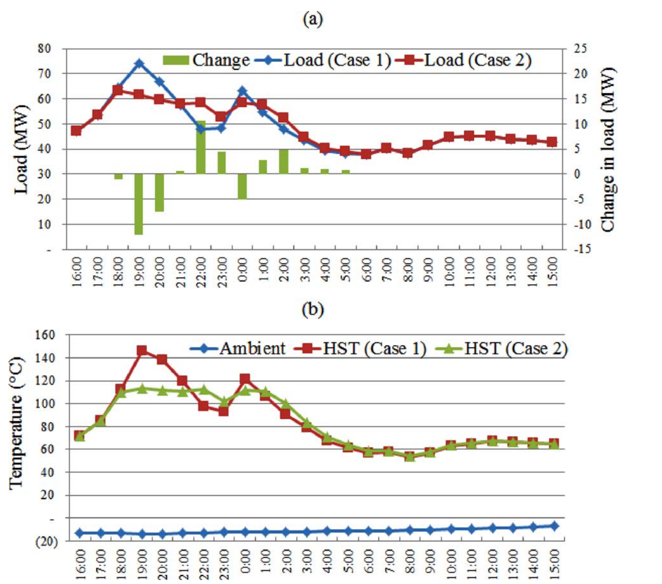

Fig. 4. Load and temperature curves of scenario 5's peak day for the primary substation transformer. (a) Transformer load. (b) Hottest-spot and ambient temperature.

not violated. To increase loading of more than 148% (scenario 3), DR is required. For scenario 4, the HST reaches 115 °C (Case 1), that is, 5°C above the limit. DR activation reduces the HST to the required level. DR is also able to limit HST to 110 °C for scenarios 5, 6, and 7.

In scenario 7, an 85 °C decrease in HST is achieved. This decrease is obtained by 38% reduction in peak demand. In this scenario, the average load is 14% higher compared to scenario 3. For loading more than that of scenario 7 (192%), the objective of reducing HST to 110 °C is not attainable with available flexible load. The decrease in LOL of the transformer due to DR is also considerable (3.81%) in this scenario.

The amount of load deferred for SS4 scenarios is given in Table VII. In all of the scenarios, the major contributor toward flexible load is electric heating. Direct electric heaters demand postponement capability of one hour is assumed which can be noticed in the results. Demand deferment increases with an increase in the reduction of HST. For scenario 7, 0.837% of annual demand is deferred.

The results for the SS10 transformer (cluster C2) are presented in Table VIII. In scenarios 1 through 3, the maximum HST limit is not violated. DR is required to increase loading

TABLE VII
ANNUAL LOAD TRANSFER IN CASE 2 FOR THE SS4 TRANSFORMER.

Scenario (Case 2)	Total demand shift under DR in a year (kWh)						
	1 h	2 h	3 h	4 h	5 h	Total	% of W_a
4	75	9	7	5	4	99	0.001
5	4 349	167	132	93	39	4 779	0.065
6	14 603	531	419	297	125	15 976	0.204
7	65 215	1 780	1 831	2 429	774	72 029	0.837

of more than 157% (scenario 3). For scenario 4, HST reaches 115 °C (Case 1), that is, 5 °C above the limit. DR activation reduces the HST to the required level. DR is also able to limit HST to 110 °C for scenarios 5, 6, and 7. In scenario 7, a 32 °C decrease in HST is achieved. This decrease is obtained by 22% reduction in peak demand. In this scenario, average load is 5% higher compared to scenario 3. For loading more than that of scenario 7 (177%), the objective of reducing HST to 110 °C is not achievable with available DR.

The decrease in maximum HST in this transformer is lower compared to that of SS4. It is because of less DR potential in this area, due to the absence of electric heating. The transformer LOL is small due to a low load factor, ambient temperature, and not very high peak loading. The ambient temperature corresponding to maximum HST is around −14 °C.

The amount of load deferred for SS10 scenarios is given in Table IX. The maximum demand deferment is 0.009% of yearly demand (in scenario 7).

The results for the SS15 (cluster C3) are presented in Table X. DR is required to increase loading of more than 139% (scenario 3). For scenario 4, HST reaches 121 °C (Case 1), that is, 11 °C above the limit. DR activation reduces the HST to the required level. In scenario 7, a 77 °C decrease in HST is achieved. This decrease is obtained by 31% reduction in peak demand. In this scenario, the average load is 12% higher compared to scenario 3. The decrease in maximum HST in this transformer is comparable to that of SS4. It is due to the DR potential of GSHP in this area. The LOL of the transformer is also reduced considerably in Case 2.

The amount of load deferred for SS15 scenarios is given in Table XI. The maximum demand deferment is 0.23% of yearly demand (in scenario# 7). The load postponed under DR in this case is less than that of SS4 and more than that of SS10.

The summary of maximum acceptable loading of all secondary substation transformers in the network is listed in Table XII.

TABLE VIII
CASE STUDY RESULTS FOR THE SS10 TRANSFORMER

Scenario	AverageLoad (p.u.)	Case 1 (without DR)			Case 2 (with DR)			Difference		
		Peak Load (p.u.)	HST max (°C)	LOL (%)	Peak Load (p.u.)	HST max (°C)	LOL (%)	Peak Load (p.u.)	HST max (°C)	LOL (%)
1	0.21	1.00	45	0.00002	1.00	45	0.00002	-	-	-
2	0.27	1.25	67	0.00005	1.25	67	0.00005	-	-	-
3	0.33	1.57	110	0.00124	1.57	110	0.00123	-	-	-
4	0.34	1.60	115	0.00183	1.56	110	0.00149	0.04	5	0.00034
5	0.35	1.65	123	0.00353	1.56	110	0.00220	0.09	12	0.00133
6	0.36	1.70	131	0.00692	1.55	110	0.00353	0.15	20	0.00338
7	0.38	1.77	142	0.01791	1.55	110	0.00714	0.22	32	0.01077
8	0.38	1.80	147	0.02697	1.58	114	0.01059	0.22	33	0.01638

These values are for both cases (with and without DR) under a maximum-allowed HST limit of 110 °C. The corresponding load shifting required for Case 2 is shown in Fig. 5 where the line graph represents the annual demand shift required as a percentage of total annual load and the percentage share of each demand shift duration (1–5 h) is displayed by stacked columns. It can be observed from Table XII that clusters C1, C3, and C4 transformers (of SS# 1, 2, 3, 4, 6, 7, 12, 15, and 16) which supply power to DE, GSHP, and STORE dominant areas benefit the most from DR. The potential for an increase of loading on these transformer ranges from 28% to 46% for peak loading, and a corresponding increase in average load is 11% to 14%. However, the GSHP dominant area transformers (cluster C3) require less demand deferment since only peak spikes elimination is needed. Demand delay for 1 h of electric heating devices constitutes a major share of DR in cluster C1 and C3 transformers (Fig. 5).

Cluster C2 transformers (of SS# 8, 10, 11, 13, and 14) supplying power to DIST dominant areas are at least benefitted by DR. The potential for increase of loading on these transformers ranges from 15% to 21% for peak loading, and a corresponding increase in average load is 4% to 5%. The benefit of DR for cluster C4 transformers (of SS# 5 and 9), which are connected to areas consisting of a mix of district and electrically heated homes, is between two other types. The potential for an increase of loading on these transformers is about 25% for peak loading, and a corresponding increase in average load is 8%. Electric storage heaters in cluster C4 transformers and the absence of electric heating in cluster C2 transformers are the main reason for high-demand delay duration.

The greater benefit for an electrically heated area is due to its higher DR potential of electric heaters, and the lack of flexible devices in a district heated area is the reason why it is less beneficial.

From the results, the following inferences can be drawn:

- The loading on the transformers can be significantly increased (up to 46% for peak load and 14% for average load). The increased loading can counter the load growth; it may be used to defer or avoid the investments of replacement and new transformers. Considering the transformer cost of U.S.$87/kVA [25], a substantial amount of U.S.$1.9 million can be saved by DR in distribution transformers of the test network.
- The proposed algorithm-based loading increase is achieved without significant LOL of the transformers since the hottest spot is limited to a certain level, which is responsible for transformer aging.
- Transformer utilization improvement is not the same for all transformers. It depends on the load profile and DR capability of connected customers. Therefore, investments for supporting the DR infrastructure will be most beneficial in electrically heated areas.

TABLE IX
ANNUAL LOAD TRANSFER IN CASE 2 FOR THE SS10 TRANSFORMER

Scenario (Case 2)	Total demand shift under DR in a year (kWh)						
	1 h	2 h	3 h	4 h	5 h	Total	% of W_a
4	16	16	12	9	7	59	0.001
5	85	28	17	12	9	150	0.003
6	168	30	18	12	10	238	0.005
7	283	57	64	42	36	483	0.009

In the present systems, price-based DR is usually used to decrease the total energy cost of electricity. In some cases, the peak load may increase if DR is optimized only for savings in the electricity bill. The proposed approach in this paper is useful to obtain a capacity benefit through DR which is required occasionally (only during peak days). Thus, on normal days, DR should be planned to minimize energy cost whereas in peak days, it should be used for capacity gain. However, further research is required for the optimum division of DR for its capacity and price benefits.

VI. CONCLUSION

This paper has examined the possibility of transformer utilization improvement with DR. The HST-based DR optimization algorithm was proposed to find the implied impact. The proposed model was used to perform a detailed study on all of the transformers in a typical Finnish residential area distribution network that supplies power to various primary heating-type households. Numerical results were obtained for two cases, with and without DR. By investigating the results, it was concluded that the loading of the transformers can be increased significantly without sacrificing the life of the transformer. Furthermore, the results show that utilization gain is proportional to the DR capability of the load.

With higher proliferation of residential DGs, the overloads might be observed more often (at peak load and peak generation) by few secondary distribution transformers. In the

TABLE X
CASE STUDY RESULTS FOR THE SS15 TRANSFORMER

Scenario	AverageLoad (p.u.)	Case 1 (without DR) Peak Load (p.u.)	HST max (°C)	LOL (%)	Case 2 (with DR) Peak Load (p.u.)	HST max (°C)	LOL (%)	Difference Peak Load (p.u.)	HST max (°C)	LOL (%)
1	0.31	1.00	59	0.00003	1.00	59	0.00003	-	-	-
2	0.38	1.25	91	0.00026	1.25	91	0.00026	-	-	-
3	0.43	1.39	110	0.00180	1.39	110	0.00180	-	-	-
4	0.44	1.45	121	0.00439	1.45	110	0.00332	0.00	11	0.00106
5	0.49	1.60	147	0.04234	1.46	110	0.01456	0.14	37	0.02778
6	0.52	1.70	165	0.19019	1.46	110	0.03407	0.24	55	0.15612
7	0.55	1.81	187	0.96142	1.50	110	0.07889	0.31	77	0.88253
8	0.56	1.83	191	1.28476	1.54	113	0.11349	0.29	78	1.17127

TABLE XI
ANNUAL LOAD TRANSFER IN CASE 2 FOR THE SS15 TRANSFORMER.

Scenario (Case 2)	Total demand shift under DR in a year (kWh) 1 h	2 h	3 h	4 h	5 h	Total	% of W_a
4	89	22	14	12	11	147	0.002
5	1 203	194	193	134	114	1 838	0.027
6	4 189	483	509	417	392	5 990	0.082
7	13 495	783	968	1 099	1 478	17 823	0.230

TABLE XII
MAXIMUM ACCEPTABLE LOADING AND DEMAND SHIFT REQUIREMENT FOR SECONDARY SUBSTATION TRANSFORMERS

SS#	Case 1 (without DR) Peak Load (p.u.)	Average Load (p.u.)	Case 2 (with DR) Peak Load (p.u.)	Average Load (p.u.)	Load Shift (% of W_a)	Difference Peak Load (p.u.)	Average Load (p.u.)
1	1.46	0.50	1.77	0.61	0.543	0.31	0.11
2	1.47	0.49	1.84	0.62	0.786	0.37	0.12
3	1.42	0.50	1.72	0.61	0.454	0.30	0.11
4	1.48	0.47	1.92	0.61	0.837	0.44	0.14
5	1.37	0.47	1.61	0.56	0.113	0.24	0.08
6	1.43	0.52	1.73	0.63	0.602	0.30	0.11
7	1.47	0.49	1.82	0.61	0.626	0.35	0.12
8	1.44	0.43	1.61	0.48	0.042	0.17	0.05
9	1.49	0.50	1.74	0.58	0.179	0.25	0.08
10	1.57	0.33	1.77	0.38	0.009	0.20	0.04
11	1.51	0.29	1.71	0.33	0.007	0.20	0.04
12	1.50	0.46	1.96	0.60	0.937	0.46	0.14
13	1.45	0.39	1.60	0.43	0.018	0.15	0.04
14	1.50	0.34	1.71	0.38	0.017	0.21	0.05
15	1.39	0.43	1.81	0.55	0.230	0.42	0.13
16	1.44	0.46	1.72	0.57	0.186	0.28	0.12

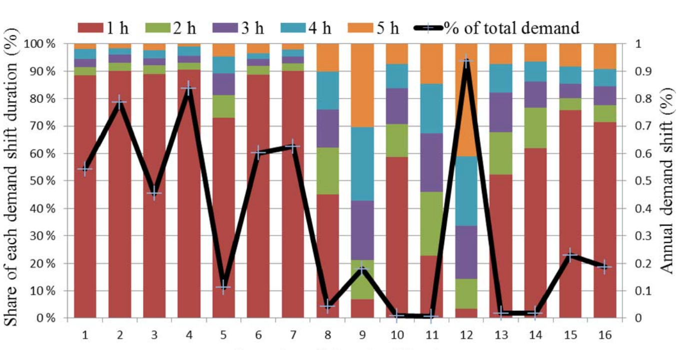

Fig. 5. Percentage share of each demand shift duration (columns) and total annual demand delay (line) for a maximum utilization increase for secondary distribution substation transformers.

following study, analysis will be extended by considering stochastic and uncertain output of residential DGs. Further study will also analyze transformers present in different conditions (e.g., cabins and indoor). The availability of flexible loads for shifting depends on the customers' acceptance. Also, some level of customer comfort is compromised with these interruptions. In the future, the analysis will be improved by considering the uncertainties associated with flexible loads and calculating customer comfort indices. Furthermore, electric-vehicle loads will also be incorporated in the analysis since a high penetration of them are anticipated for the future.

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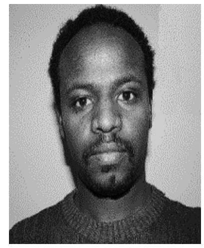

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