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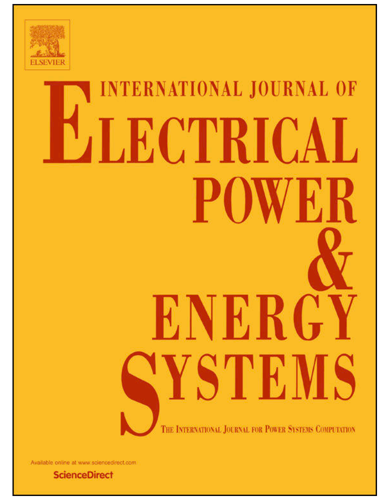

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Analysis of COVID-19 Effect on Residential Loads and Distribution Transformers

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Highlights
- The impact of COVID-19 on residential loads and distribution transformer is analyzed.
- Due to COVID-19 the energy consumptions of residential consumers have increased.
- The residential transformer gets vulnerable due to COVID-19 situation.
- BTM source can mitigate adverse effect of increased load on distribution transformer.

Abstract

This paper analyzes the impact of COVID-19 pandemic situation on residential loads and local distribution transformer. The transformers' operating condition in terms of hottest winding temperature, top oil transformer, loss of life (%LOL) are analyzed considering different loads and harmonics content in the transformer currents. Based on these analyses, safe operating conditions of transformer are derived. Six types of consumers having different consumption patterns and different type of residential loads are considered for the analysis. In order to mitigate the adverse impacts of COVID-19 on loads and distribution transformer, the use of behind-the-meter (BTM) photovoltaic (PV) source, battery energy storage and electric vehicle, load scheduling, less utilization of loads that have distortion factors during office hours are proposed. A performance comparison has been made without and with considering the proposed BTM solution, load scheduling and loads having distortion factors. Simulation results show that, due to lockdown situation of COVID-19 issue, the residential loads consumptions increase during office hours and hence the local distribution transformer gets affected. Also, the proposed BTM solution, load scheduling and less utilization of loads having harmonic distortion can cope up with the increased energy consumptions during office hours.

Index Terms— **Behind-the-meter (BTM) technology, distribution transformer, novel corona virus (COVID-19), residential loads, etc.**

I. Introduction

THE novel Corona virus (COVID-19) has impacted every aspect of human life not only in USA but also all over the world. The number of deaths due to COVID-19 has been piling up each day. Fig. 1 shows the COVID-19 statistics from March 2020 to October 27th 2020 in Shelby county, Memphis, Tennessee, USA [1]. Many states in USA have declared emergency and imposed orders to be in partial/fully lockdown conditions. In order to remain safe, people were forced to stay at home, work from home wherever possible and the educational institution, public places were closed in Memphis from March 24th, 2020. Because of people's staying at home, the energy consumption patterns of residential buildings have changed. Specially, during the office hours, the load consumptions in buildings have increased dramatically. Fig. 2 shows the average load consumptions per half an hour of a house located at Memphis city for the consecutive two months (March and April 2020). The data indicates that significant amount of load consumptions increased during the office hours (specially from about noon to 6 pm) due to the lockdown situation in April 2020.

It is noteworthy that the increased load consumptions at houses due to COVID-19 situation will impact the residential distribution transformers. In particular, load patterns of distribution transformers will change. Even the distribution transformers may be overloaded. The safe operation of residential transformers depends on various factors such as temperature, loads, fault, etc. The hottest winding temperature of transformer, top oil temperature, and loss of life due to insulation aging are important features that indicate the safe operational range and life span of residential distribution transformers [2]-[3]. Due to overloading, the distribution transformers may get damaged [4]-[6]. Moreover, along with load magnitude, the harmonic contents in load current have severe effect on transformers' hottest temperature rise, top oil temperature rise, loss of life and transformer failure [7]-[8]. Therefore, the operation of distribution transformer due to change in load patterns at residential buildings needs attention and should be investigated. If the lockdown situation due to this COVID-19 continues for a long time, the local distribution transformers will have much chance of getting overloaded. Therefore, it is important to analyze the potential impact of increased residential energy consumptions during office hours on distribution transformers and explore appropriate solutions to mitigate the adverse impacts.

Based on the above background, this paper analyzes the energy pattern changes of residential loads, especially during the office hours (9.0 am to 6.00 pm) and their impacts on the residential transformers in terms of hottest winding temperature, top oil temperature, and percentage loss of life (%LOL). And this is the novelty of this work. Mathematical modeling of hottest winding temperature of transformer, top oil temperature, and loss of life are utilized to conduct the proposed analysis. Moreover, to mitigate the adverse effects of increased energy consumptions at houses on distribution transformers, the operation of the behind-the-meter (BTM) sources such as the photovoltaic (PV) power, battery energy storage, and electric vehicle, loads scheduling, less usage of loads that produce high harmonic currents, during office hours are proposed as solutions. The objective here is that the proposed mitigation steps will meet the increased amount of energy consumptions or at least fraction of it so that loads on distribution transformers decrease and also the percentage loss of life (%LOL) of the residential transformers gets reduced. It is considered that the grid will provide power at houses as usual, however, the PV system and the electric vehicle together will be able to provide the increased amount of energy consumptions during office hours. The battery energy storage will be charged by the excess day time PV power. And the electric vehicle will be charged during nighttime only by the battery energy storage.

For the analysis, six types of energy consumptions data having different types of loads and source to power the loads, are collected from the smart meters data available in MLGW web accounts of six consumers who live at Memphis city, TN, USA. The main contributions of this work are summarized below.

1) The impact of COVID-19 lockdown situation on residential loads and distribution transformer during office hours is analyzed.
2) Mathematical formulations have been derived to calculate hottest spot temperature of the transformer winding, top oil temperature and the loss of life.
3) The BTM source, battery energy storage and electric vehicle, load scheduling, less usage of loads that produce high harmonic currents, are considered as solutions to mitigate the adverse effects of increased load on distribution transformer.

The organization of this paper is as follows. Section II provides a mathematical formulation to calculate hottest spot temperature of the transformer winding, top oil temperature and the loss of life. Section III explains the impact of COVID-19 on residential

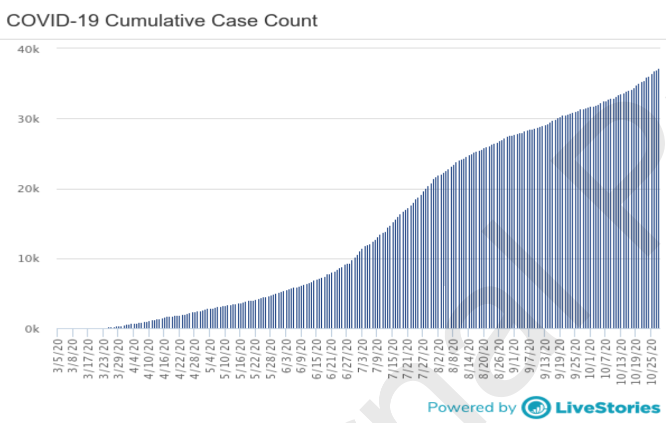


Fig. 1. COVID-19 statistics in Shelby county, Memphis, TN, USA [1].

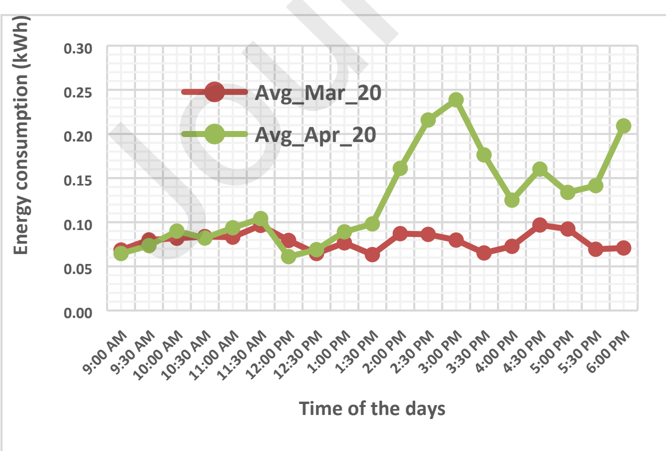


Fig. 2. Energy consumption of consecutive two months of 2020 for consumer 1.

loads and distribution transformer through simulations. Section IV describes the method to mitigate the adverse effects of increased load on distribution transformer. Finally, section V provides conclusions on this work and future recommendation.

II. Formulation of Effect of Residential Loads on Local Distribution Transformers

In this work, two types of conditions are considered. For the first case, no harmonics are considered in the load currents, and for the second case the load currents are considered with different harmonic contents. Based on these two cases, the effect of increased loads on distribution transformers in terms of hottest spot temperature of transformer winding, top oil temperature and the percentage loss of life (%LOL) due to insulation aging are analyzed. The total amount of current (per unit) that the transformer needs to provide can be expressed by the following equation:

$$T_{i-pu} = \frac{I_{c,h} \times n \times P}{I_{Trated}} \qquad (1)$$

Where, $I_{c,h}$ is the current consumed by one consumer at any given hour h, and n is the number of apartments that are connected to the same residential transformer. P is the factor which defines the likelihood of consumption of other apartment as compared to the currents of the consumer or apartment under consideration. P value of 0.5 represents that the transformer load will be half of n times higher rather than n times whereas P value 1.5 represents the transformer load to be 1.5n times higher rather than n times with respect to one consumer considered. Moreover, P value of 1 represents that the transformer load will be exactly n times with respect to one consumer considered.

A. Hottest Spot Temperature of the Windings, Top Oil Temperature and Percentage Loss of Life of Transformer Calculation without Considering Harmonics

Due to loading, the winding hot-spot temperature (HST) and aging of transformer need to be calculated. The transformer winding HST, θ_H, can be calculated by using the following equations [9].

$$\theta_H = \theta_A + \Delta\theta_{TO} + \Delta\theta_H \qquad (2)$$

Where, θ_A represents the ambient temperature at any given time. $\Delta\theta_{TO}$ and $\Delta\theta_H$ represent the top oil rise over the ambient temperature and winding hottest spot rise over the top-oil temperature, respectively. The top oil temperature can be represented as:

$$\theta_{TO} = \theta_A + \Delta\theta_{TO} \qquad (3)$$

$\Delta\theta_{TO}$ and $\Delta\theta_H$ can be expressed by the following two equations:

$$\Delta\theta_{TO} = (\Delta\theta_{TO,U} - \Delta\theta_{TO,I})\left(1 - exp^{-\frac{t}{T_{TO}}}\right) + \Delta\theta_{TO,I} \qquad (4)$$

$$\Delta\theta_H = (\Delta\theta_{H,U} - \Delta\theta_{H,I})\left(1 - exp^{-\frac{t}{T_W}}\right) + \Delta\theta_{H,I} \qquad (5)$$

Where, $\Delta\theta_{TO,U}$ and $\Delta\theta_{TO,I}$ represent the ultimate and initial top oil rise, respectively, over ambient temperature, and T_{TO} is the oil time constant. Similarly, $\Delta\theta_{H,U}$ and $\Delta\theta_{H,I}$ represent the ultimate and initial hottest spot rise, respectively, over top oil temperature, and T_W is the winding time constant. Moreover, $\Delta\theta_{TO,U}$ and $\Delta\theta_{H,U}$ can be calculated from the following two equations:

$$\Delta\theta_{TO,U} = \Delta\theta_{TO,R}\left[\frac{K_U^2 R + 1}{R + 1}\right]^n \qquad (6)$$

$$\Delta\theta_{H,U} = \Delta\theta_{H,R} K_U^{2m} \qquad (7)$$

The aging acceleration factor (F_{AA}) of the thermally upgraded paper can be represented by the following equation:

$$F_{AA} = exp^{\left(\frac{15000}{383} - \frac{15000}{\theta_H + 383}\right)} \qquad (8)$$

The equivalent aging factor can be represented as:

$$F_{EQA} = \frac{\sum_{r=1}^{j} F_{AA,r}\Delta t_r}{\sum_{r=1}^{j} \Delta t_r} \qquad (9)$$

Where r represents the index number of time interval Δt. The percentage loss of life (%LOL) for operation of t hours can be represented by (10). In this %LOL calculation, the insulation life of transformer is considered to be 180000 hours.

$$\%LOL = \frac{F_{EQA} \times t \times 100}{Normal\ insulation\ life} \quad (10)$$

B. Hottest Spot Temperature of the Windings, Top Oil Temperature and Percentage Loss of Life of Transformer Calculation Considering Harmonics

The transformer loss for any load current having harmonics can be defined by the following equation [11]:

$$P_{LL} = \left(\frac{I_L}{I_R}\right)^2 (P_{DC-R} + F_{HL} \times P_{EC-R} + F_{HL-STR} \times P_{OSL-R}) \quad (11)$$

Where, P_{LL}, P_{DC-R}, P_{EC-R}, and P_{OSL-R} represent load power loss at any load current I_L, rated winding dc loss, rated winding eddy current loss, and other rated stray loss, respectively, and I_R is the rated transformer current. The harmonic loss factor (F_{HL}) and harmonic loss factor for other stray loss (F_{HL-STR}) are defined by the following two equations:

$$F_{HL} = \frac{\sum_{h=1}^{\infty}\left(\frac{I_h}{I_1}\right)^2 h^2}{\sum_{h=1}^{\infty}\left(\frac{I_h}{I_1}\right)^2} = \frac{\sum_{h=1}^{\infty}\left(\frac{I_h}{I_L}\right)^2 h^2}{\sum_{h=1}^{\infty}\left(\frac{I_h}{I_L}\right)^2} \quad (12)$$

$$F_{HL-STR} = \frac{\sum_{h=1}^{\infty}\left(\frac{I_h}{I_1}\right)^2 h^{0.8}}{\sum_{h=1}^{\infty}\left(\frac{I_h}{I_1}\right)^2} = \frac{\sum_{h=1}^{\infty}\left(\frac{I_h}{I_L}\right)^2 h^{0.8}}{\sum_{h=1}^{\infty}\left(\frac{I_h}{I_L}\right)^2} \quad (13)$$

In per-unit, the load power loss can be expressed as the following [11]-[12]:

$$P_{LL}(pu) = (I(pu))^2(1 + F_{HL} \times P_{EC-R}(pu) + F_{HL-STR} \times P_{OSL-R}(pu)) \quad (14)$$

Where, I_R and P_{DC-R} are taken as base for current and power loss, respectively. The rated load loss can be expressed by the following equations:

$$P_{LL-R} = (P_{DC-R} + P_{EC-R} + P_{OSL-R}) \quad (15)$$

$$P_{LL-R}(pu) = (1 + P_{EC-R}(pu) + P_{OSL-R}(pu)) \quad (16)$$

$\Delta\theta_{TO,U}$ and $\Delta\theta_{H,U}$ can be calculated by following two equations [11]-[12]:

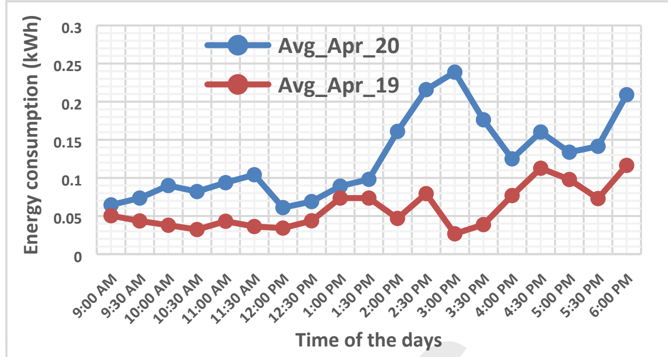
$$\Delta\theta_{TO,U} = \Delta\theta_{TO,R}\left(\frac{P_{LL} + P_{NL}}{P_{LL-R} + P_{NL}}\right)^{0.8} \quad (17)$$

$$\Delta\theta_{H,U} = \Delta\theta_{H,R}\left(\frac{P_{LL}(pu)}{P_{LL-R}(pu)}\right)^{0.8} \quad (18)$$

III. Impact Analysis of COVID-19 on Residential Loads and Distribution Transformer through Simulations

A. Simulation Data and Conditions

As already mentioned, in this COVID-19 situation, the load consumption patterns among different classes of people have changed, especially during office hours. In order to demonstrate this situation, six types of consumers have been considered. First, we considered a family (consumer 1) where both husband and wife work and their son studies at a school in Memphis city. The second type of data was collected from a house (consumer 2) where all residents are Ph.D. students who normally work from 10 am to 6 pm in a research lab located at the University of Memphis and during lockdown they stayed at home. The third data was collected from a family having three members (husband, wife and a baby boy). The husband works normally during the office hours and other members stay at home, but during lockdown all stayed at home. The fourth and fifth data were collected from two apartments having three and two PhD students, respectively, who normally spend their office hours (10 am to 6 pm) in the university labs but during the lockdown situation they were forced to stay at home. The sixth data was collected from a family having four members (husband, wife and two daughters). The husband works during the office hours and the elder daughter goes to school in normal times, but all stayed at home during the lockdown.



(a)

(b)

(c)

(d)

Fig. 3. Energy consumption of consecutive two years of (a) April (b) May (c) June (d) July months for consumer 1.

B. Impact of COVID-19 on Residential Energy Consumption

The average energy consumptions per half an hour of different months of consecutive two years (2019 and 2020) for consumer 1 are shown in Fig. 3, where the data reflects the fact that the energy consumption of consumer 1 has indeed increased for some parts of the office hours (i.e., for all office hours for April , 9.00 am to 3.30 pm for May, 9.00 am to 12.30 pm and 4.00 pm to 6.00

pm for June, and the entire office hours for July month) as compared to previous year.

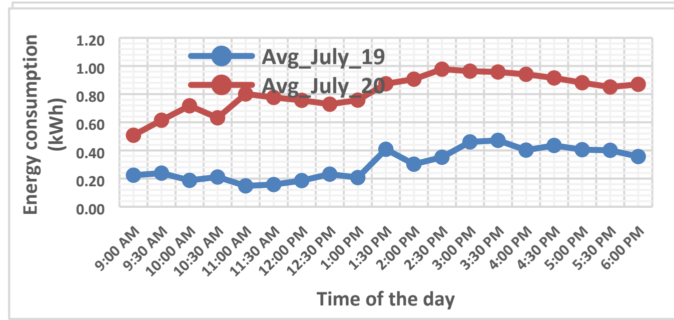
TABLE I: ENERGY CONSUMPTION COMPARISON FOR CONSUMER 1

Time	Mar_20 (kWh)	Maximum_Mar_20 (kWh)	Apr_20 (kWh)	Maximum_Apr_20 (kWh)	% Increase _kWh
9:00 AM	0.069	0.150	0.065	0.220	-5.78
9:30 AM	0.080	0.235	0.074	0.145	-8.07
10:00 AM	0.082	0.185	0.090	0.465	9.92
10:30 AM	0.084	0.170	0.082	0.145	-1.99
11:00 AM	0.083	0.170	0.094	0.385	12.78
11:30 AM	0.096	0.670	0.104	0.390	7.99
12:00 PM	0.079	0.275	0.061	0.120	-23.1
12:30 PM	0.065	0.135	0.069	0.330	6.77
1:00 PM	0.077	0.305	0.089	0.350	16.30
1:30 PM	0.063	0.160	0.098	0.305	54.93
2:00 PM	0.087	0.240	0.161	0.600	84.93
2:30 PM	0.086	0.320	0.216	0.695	150.2
3:00 PM	0.080	0.230	0.239	1.035	199.2
3:30 PM	0.065	0.140	0.176	0.725	170.2
4:00 PM	0.073	0.255	0.125	0.575	71.92
4:30 PM	0.097	0.845	0.160	0.950	65.38
5:00 PM	0.092	0.875	0.134	0.625	44.92
5:30 PM	0.069	0.200	0.141	0.460	103.9
6:00 PM	0.071	0.185	0.209	0.610	195.3

TABLE II: CURRENT CONSUMPTION COMPARISON FOR CONSUMER 1

Time	I_March (A)	I_April (A)	kVar_March (kVAR)	kVar_April (kVAR)	% Increase _Current
9:00 AM	1.344	1.266	0.085	0.080	-5.78
9:30 AM	1.569	1.442	0.099	0.091	-8.07
10:00 AM	1.605	1.765	0.101	0.112	9.92
10:30 AM	1.642	1.609	0.104	0.102	-1.99
11:00 AM	1.630	1.838	0.103	0.116	12.78
11:30 AM	1.891	2.042	0.120	0.129	7.99
12:00 PM	1.556	1.197	0.098	0.076	-23.10
12:30 PM	1.266	1.352	0.080	0.085	6.77
1:00 PM	1.503	1.748	0.095	0.111	16.30
1:30 PM	1.242	1.924	0.079	0.122	54.93
2:00 PM	1.708	3.158	0.108	0.200	84.93
2:30 PM	1.691	4.232	0.107	0.268	150.24
3:00 PM	1.565	4.681	0.099	0.296	199.22
3:30 PM	1.279	3.456	0.081	0.218	170.29
4:00 PM	1.426	2.451	0.090	0.155	71.92
4:30 PM	1.900	3.141	0.120	0.199	65.38
5:00 PM	1.810	2.623	0.114	0.166	44.92
5:30 PM	1.360	2.774	0.086	0.175	103.90
6:00 PM	1.389	4.101	0.088	0.259	195.29

The increase in the energy consumption per half an hour and the percentage of energy consumption increase for March and April 2020, along with the maximum demands (kWh) for both months, have been tabulated in TABLE I. The last column of TABLE I represents the percentage of energy consumption increase in April 2020 as compared to that of March 2020. The positive value in the increase column indicates the energy consumption



(a)

(b)

(c)

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(e)

Fig. 5. Energy consumption of consecutive two years of (a) March (b) April (c) May (d) June (e) July months for consumer 3.

has increased due to the presence of the residents at the house during the office hours. Moreover, the current increase data for March and April 2020 have been tabulated in TABLE II. The third and fourth column of TABLE II represent the reactive power in kVar consumption for March and April, respectively, in 2020. The current is calculated from the kWh data shown in Table I. For example, the energy consumption for half an hour at 9.00 am is 0.069 kWh for March. The supply voltage is considered 120 V for a single-phase system. Now if the kWh value is divided by half an hour and the voltage magnitude, the current magnitude of 1.344 A (assuming 0.85 power factor lagging) can be obtained.

TABLE III: ENERGY CONSUMPTION COMPARISON FOR CONSUMER 2

Time	Mar_20 (kWh)	Maximum_Mar_20 (kWh)	Apr_20 (kWh)	Maximum_Apr_20 (kWh)	% Increase _kWh
1:00 PM	0.980	2.920	0.883	2.770	-9.89
1:30 PM	0.885	2.290	1.026	3.480	15.91
2:00 PM	0.809	1.980	1.294	2.365	59.86
2:30 PM	0.634	2.450	1.123	2.440	77.25
3:00 PM	0.628	2.460	1.122	2.960	78.82
3:30 PM	0.655	2.020	1.351	2.625	106.17
4:00 PM	0.517	1.310	1.234	2.510	138.56
4:30 PM	0.582	2.230	0.962	2.690	65.21
5:00 PM	0.553	2.070	0.941	2.025	70.32
5:30 PM	0.591	2.530	1.033	2.170	74.77
6:00 PM	0.511	1.390	0.599	1.540	17.33

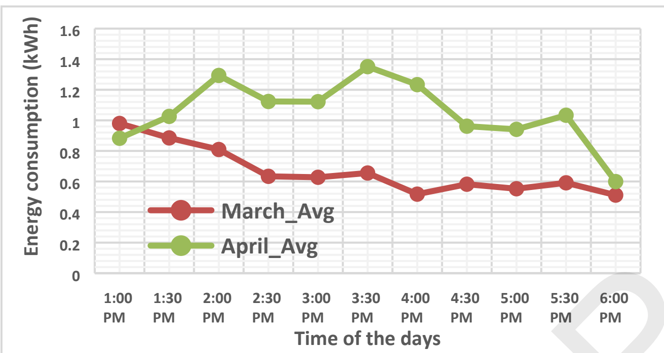
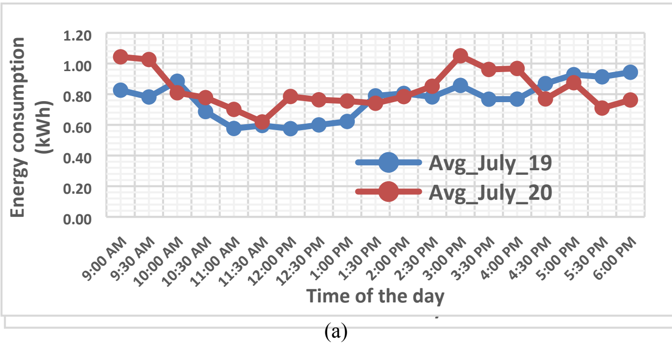


Fig. 4. Energy consumption for consecutive two months in 2020 for consumer 2.

TABLE IV: CURRENT CONSUMPTION COMPARISON FOR CONSUMER 2

Time	I_March (A)	I_April (A)	kVar_ March (kVAR)	kVar_ April (kVAR)	% Increase _Current
1:00 PM	19.208	17.308	1.214	1.094	-9.89
1:30 PM	17.353	20.114	1.097	1.272	15.91
2:00 PM	15.866	25.364	1.003	1.603	59.86
2:30 PM	12.426	22.026	0.786	1.392	77.25
3:00 PM	12.304	22.002	0.778	1.391	78.82
3:30 PM	12.851	26.495	0.812	1.675	106.17
4:00 PM	10.139	24.187	0.641	1.529	138.56
4:30 PM	11.413	18.856	0.721	1.192	65.21
5:00 PM	10.833	18.452	0.685	1.166	70.32
5:30 PM	11.593	20.261	0.733	1.281	74.77
6:00 PM	10.016	11.752	0.633	0.743	17.33

For the consumer 2, the residents started living in the apartment this year (2020), and therefore no data of previous year is available. During the COVID-19 situation, their energy consumption has increased from 1.00 pm to 6.00 pm as shown in Fig. 4. Moreover, one of the residents moved to another apartment in the middle of May, therefore, only March and April months are considered for consumer 2. The increase in energy consumption and the percentage of increase of energy



(a)

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Fig. 6. Energy consumption of consecutive two years of (a) March (b) April (c) May (d) June (e) July months for consumer 4.

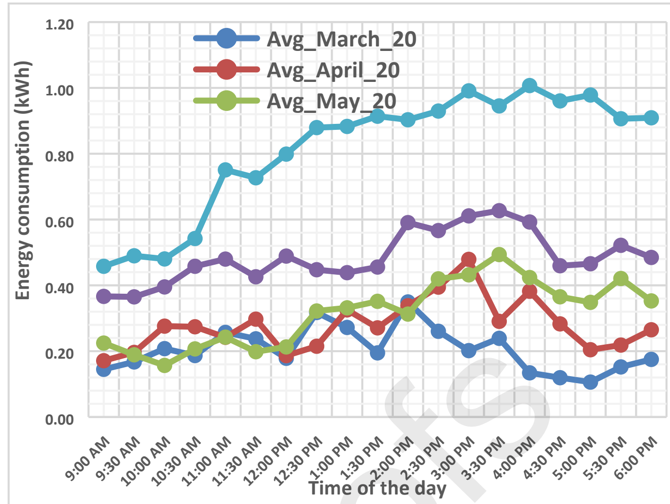
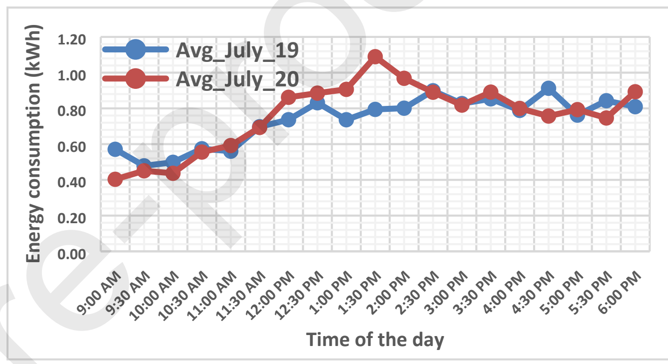


Fig. 7. Energy consumption for consumer 5 in 2020 from March to July months.



(a)

(b)

(c)

Fig. 8. Energy consumption of consecutive two years of (a) April (b) June (c) July months for consumer 6.

consumption have been tabulated in TABLE III for consumer 2 including the maximum demand for both March and April month in 2020. Also, the current consumption comparison is shown in TABLE IV along with reactive power required for both March and April month in 2020. The current is calculated by the same way as already described for consumer 1.

Moreover, the energy consumption pattern of consumer 3 for different months of the consecutive two years are shown in Fig. 5. Fig. 5 indicates that the energy consumption for consumer 3 is higher in 2020 as compared to in 2019 for almost all hours for all months from March to July.

The energy consumption patterns for consumer 4 from March to July months for the consecutive two years are shown in Fig. 6. Like the consumer 3, the energy consumption for the consumer 4 for all the considered months are higher in 2020 as compared to in 2019.

For the consumer 5, only 2020 energy consumptions data are available. Therefore, energy consumptions from March to July in 2020 are shown in Fig. 7.

From Fig. 7, it can be said that, the energy consumptions in April and May get higher as compared to that of March after 2.00 pm. For the months of June and July, the energy consumptions are always higher as compared to that of March

TABLE V: PER UNIT CURRENT OF RESIDENTIAL TRANSFORMER 1 FOR THE MONTH OF APRIL 2019 (BASED ON CONSUMER 1)

Time	P											
	.5	.6	.7	.75	.8	.9	1	1.1	1.2	1.3	1.4	1.5
9:00 AM	0.237	0.285	0.332	0.356	0.380	0.427	0.475	0.522	0.569	0.617	0.664	0.712
9:30 AM	0.205	0.246	0.287	0.307	0.328	0.369	0.410	0.451	0.492	0.533	0.574	0.615
10:00 AM	0.178	0.214	0.250	0.268	0.285	0.321	0.357	0.393	0.428	0.464	0.500	0.535
10:30 AM	0.152	0.182	0.213	0.228	0.243	0.274	0.304	0.334	0.365	0.395	0.425	0.456
11:00 AM	0.203	0.244	0.284	0.304	0.325	0.365	0.406	0.446	0.487	0.528	0.568	0.609
11:30 AM	0.171	0.205	0.239	0.256	0.273	0.307	0.341	0.375	0.409	0.444	0.478	0.512
12:00 PM	0.161	0.193	0.225	0.241	0.257	0.289	0.322	0.354	0.386	0.418	0.450	0.482
12:30 PM	0.206	0.247	0.288	0.309	0.329	0.371	0.412	0.453	0.494	0.535	0.576	0.618
1:00 PM	0.346	0.415	0.485	0.519	0.554	0.623	0.692	0.761	0.831	0.900	0.969	1.038
1:30 PM	0.346	0.415	0.485	0.519	0.554	0.623	0.692	0.761	0.831	0.900	0.969	1.038
2:00 PM	0.221	0.265	0.309	0.331	0.353	0.397	0.441	0.485	0.529	0.574	0.618	0.662
2:30 PM	0.374	0.448	0.523	0.560	0.598	0.672	0.747	0.822	0.896	0.971	1.046	1.121
3:00 PM	0.125	0.151	0.176	0.188	0.201	0.226	0.251	0.276	0.301	0.326	0.351	0.376
3:30 PM	0.182	0.219	0.255	0.274	0.292	0.328	0.365	0.401	0.438	0.474	0.511	0.547
4:00 PM	0.362	0.434	0.506	0.543	0.579	0.651	0.724	0.796	0.868	0.941	1.013	1.085
4:30 PM	0.530	0.636	0.743	0.796	0.849	0.955	1.061	1.167	1.273	1.379	1.485	1.591
5:00 PM	0.461	0.553	0.645	0.691	0.737	0.829	0.922	1.014	1.106	1.198	1.290	1.382
5:30 PM	0.343	0.412	0.480	0.515	0.549	0.618	0.686	0.755	0.824	0.892	0.961	1.029
6:00 PM	0.548	0.658	0.767	0.822	0.877	0.986	1.096	1.206	1.315	1.425	1.535	1.644

TABLE VI: PER UNIT CURRENT OF RESIDENTIAL TRANSFORMER 1 FOR THE MONTH OF APRIL 2020 (BASED ON CONSUMER 1)

Time	P											
	.5	.6	.7	.75	.8	.9	1	1.1	1.2	1.3	1.4	1.5
9:00 AM	0.304	0.365	0.425	0.456	0.486	0.547	0.608	0.668	0.729	0.790	0.851	0.912
9:30 AM	0.346	0.415	0.485	0.519	0.554	0.623	0.692	0.761	0.831	0.900	0.969	1.038
10:00 AM	0.424	0.508	0.593	0.635	0.678	0.762	0.847	0.932	1.017	1.101	1.186	1.271
10:30 AM	0.386	0.463	0.541	0.579	0.618	0.695	0.772	0.850	0.927	1.004	1.081	1.158
11:00 AM	0.441	0.529	0.618	0.662	0.706	0.794	0.882	0.970	1.059	1.147	1.235	1.323
11:30 AM	0.490	0.588	0.686	0.735	0.784	0.882	0.980	1.078	1.176	1.274	1.372	1.470
12:00 PM	0.287	0.345	0.402	0.431	0.460	0.517	0.575	0.632	0.689	0.747	0.804	0.862
12:30 PM	0.324	0.389	0.454	0.487	0.519	0.584	0.649	0.714	0.779	0.844	0.909	0.973
1:00 PM	0.420	0.503	0.587	0.629	0.671	0.755	0.839	0.923	1.007	1.091	1.175	1.259
1:30 PM	0.462	0.554	0.646	0.693	0.739	0.831	0.924	1.016	1.108	1.201	1.293	1.385
2:00 PM	0.758	0.910	1.061	1.137	1.213	1.364	1.516	1.667	1.819	1.971	2.122	2.274
2:30 PM	1.016	1.219	1.422	1.524	1.625	1.828	2.031	2.234	2.438	2.641	2.844	3.047
3:00 PM	1.123	1.348	1.573	1.685	1.798	2.022	2.247	2.472	2.696	2.921	3.146	3.370
3:30 PM	0.829	0.995	1.161	1.244	1.327	1.493	1.659	1.825	1.991	2.157	2.322	2.488
4:00 PM	0.588	0.706	0.824	0.882	0.941	1.059	1.176	1.294	1.412	1.529	1.647	1.765
4:30 PM	0.754	0.905	1.055	1.131	1.206	1.357	1.508	1.658	1.809	1.960	2.111	2.262
5:00 PM	0.630	0.755	0.881	0.944	1.007	1.133	1.259	1.385	1.511	1.637	1.763	1.889
5:30 PM	0.666	0.799	0.932	0.999	1.065	1.198	1.332	1.465	1.598	1.731	1.864	1.997
6:00 PM	0.984	1.181	1.378	1.476	1.575	1.772	1.968	2.165	2.362	2.559	2.756	2.953

during office hours.

The energy consumptions comparison for various months of consecutive two years (2019 and 2020) for consumer 6 is shown in Fig. 8. From Fig. 8, it is evident that as father and elder daughter were forced to stay at home, the energy consumptions are higher from 9.00 am to 10.00 am, 12.30 pm to 3.00 pm and 4.00 pm 4.30 pm for the month of April. Similar situations are observed from 12.30 pm to 5.30 pm for the month of June and 12.00 pm to 2.00 pm for the month of July.

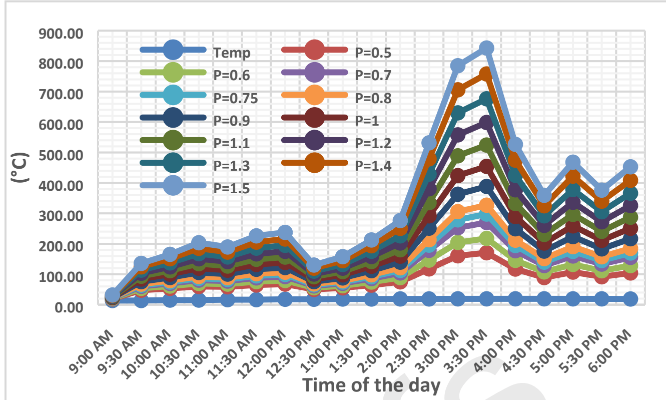


Fig. 10. Hottest spot temperature of winding of transformer 1 for month of April 2020.

C. Impact of Residential Energy Consumption Increase on Distribution Transformer

For the consumer 1 house, both electric and gas lines are connected. Therefore, some of the loads are powered by electricity and some are powered by gas. In total, there are 6 apartments for which there is a residential transformer. The transformer's rating is assumed to be 1.5 kVA. Therefore, the rated current of the transformer is 12.5 A. Based on this, the total amount of current (per unit) for different values of P are calculated using (1) for the months of April 2019 and April 2020, and are shown in TABLE V and TABLE VI, respectively.

For this study, the value of P is considered in the range of 0.5 to 1.5.

C.1) The hottest spot temperature, top oil temperature and percentage loss of life of distribution transformer without considering harmonics' presence in load current

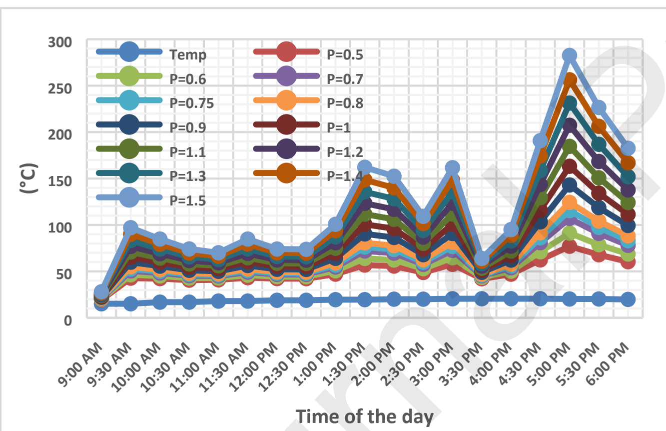


Fig. 9. Hottest spot temperature of winding of transformer 1 for month of April 2019.

According to IEEE standard C57.91-2011, the top oil temperature and hottest spot temperature should not exceed 120ºC and 200ºC, respectively, to avoid the failure of the transformer [9]. The hottest spot temperature of transformer for the month of April 2019 and April 2020 for different values of P are shown in Fig. 9 and Fig. 10, respectively. From Fig. 9, it is interesting to notice that the hottest winding temperature for the month of April in 2019 would have exceeded above 200 ºC if the P value became 1.2 or higher. However, the hottest spot temperature for month of April 2020 as shown in Fig. 10 exceeds 200ºC as the P value increases from 0.6 to upwards, which indicates the COVID-19 effect on the rise of hottest winding temperature. If this lockdown situation continues, with the increase in ambient temperature in summer, the hottest spot temperature may get even higher.

Due to COVID-19 situation the increase in temperature in April 2020 as compared to April 2019 is shown in Fig. 11. The per unit currents data are taken from TABLE V and TABLE VI for the month of April of 2019 and 2020, respectively. From Fig. 11 it is evident that the hottest winding temperature of April 2020 is higher than that of April 2019 during office hour specially from 2.30 pm to 4.00 pm. The hottest spot temperature difference exceeds 200ºC as P value increases from 0.7 to upwards in 2020, although the ambient temperature in April 2019 is higher than that of April 2020 as indicated by the negative value of temperature difference in Fig. 11. Moreover, for the transformer 1, the top oil temperature difference between the month of April 2020 and April 2019 is shown in Fig. 12. As previously discussed, the top oil temperature should not exceed 120 ºC but the top oil difference exceeds 120 ºC for P values of 0.9 or higher.

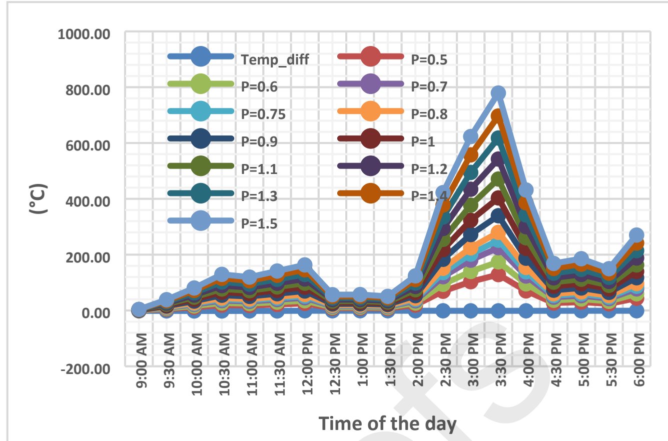


Fig. 11. Increase in hottest spot temperature of transformer 1 winding for month of April 2020 as compared to April 2019.

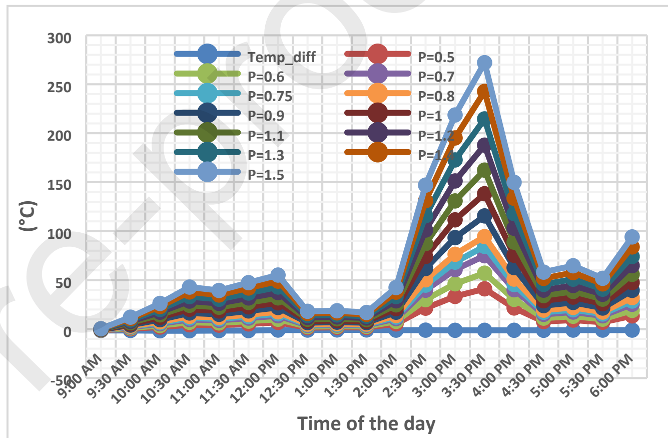


Fig. 12. Increase in top oil temperature of transformer 1 for month of April 2020 as compared to month of April 2019.

TABLE VII: PER UNIT CURRENT OF RESIDENTIAL TRANSFORMER 1 FOR THE MONTH OF APRIL 2020 (BASED ON CONSUMER 1 MAXIMUM DEMAND)

Time	P											
	.5	.6	.7	.75	.8	.9	1	1.1	1.2	1.3	1.4	1.5
9:00 AM	1.035	1.242	1.449	1.553	1.656	1.864	2.071	2.278	2.485	2.692	2.899	3.106
9:30 AM	0.682	0.819	0.955	1.024	1.092	1.228	1.365	1.501	1.638	1.774	1.911	2.047
10:00 AM	2.188	2.626	3.064	3.282	3.501	3.939	4.376	4.814	5.252	5.689	6.127	6.565
10:30 AM	0.682	0.819	0.955	1.024	1.092	1.228	1.365	1.501	1.638	1.774	1.911	2.047
11:00 AM	1.812	2.174	2.536	2.718	2.899	3.261	3.624	3.986	4.348	4.711	5.073	5.435
11:30 AM	1.835	2.202	2.569	2.753	2.936	3.304	3.671	4.038	4.405	4.772	5.139	5.506
12:00 PM	0.565	0.678	0.791	0.847	0.904	1.016	1.129	1.242	1.355	1.468	1.581	1.694
12:30 PM	1.553	1.864	2.174	2.329	2.485	2.795	3.106	3.416	3.727	4.038	4.348	4.659
1:00 PM	1.647	1.976	2.306	2.471	2.635	2.965	3.294	3.624	3.953	4.282	4.612	4.941
1:30 PM	1.435	1.722	2.009	2.153	2.296	2.584	2.871	3.158	3.445	3.732	4.019	4.306
2:00 PM	2.824	3.388	3.953	4.235	4.518	5.082	5.647	6.212	6.776	7.341	7.906	8.471
2:30 PM	3.271	3.925	4.579	4.906	5.233	5.887	6.541	7.195	7.849	8.504	9.158	9.812
3:00 PM	4.871	5.845	6.819	7.306	7.793	8.767	9.741	10.715	11.689	12.664	13.638	14.612
3:30 PM	3.412	4.094	4.776	5.118	5.459	6.141	6.824	7.506	8.188	8.871	9.553	10.235
4:00 PM	2.706	3.247	3.788	4.059	4.329	4.871	5.412	5.953	6.494	7.035	7.576	8.118
4:30 PM	4.471	5.365	6.259	6.706	7.153	8.047	8.941	9.835	10.729	11.624	12.518	13.412
5:00 PM	2.941	3.529	4.118	4.412	4.706	5.294	5.882	6.471	7.059	7.647	8.235	8.824
5:30 PM	2.165	2.598	3.031	3.247	3.464	3.896	4.329	4.762	5.195	5.628	6.061	6.494
6:00 PM	2.871	3.445	4.019	4.306	4.593	5.167	5.741	6.315	6.889	7.464	8.038	8.612

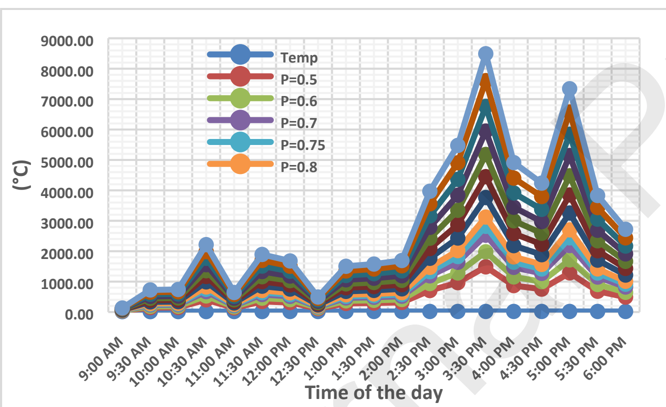


Fig. 13. Hottest spot temperature of winding of transformer 1 for month of April 2020 considering the maximum demand.

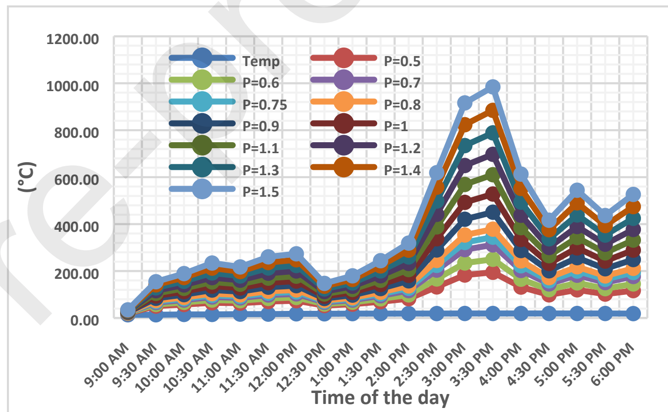


Fig. 14. Hottest spot temperature of Transformer 1winding for month of April 2020 for F_{HL} = 2.73 and F_{HL-STR} = 1.14.

TABLE VII represents the per unit current of transformer 1 based on consumer 1 maximum demands for April 2020 which are tabulated in TABLE I. Based on these per unit currents, the hottest winding temperature for transformer 1 is represented in Fig. 13 for different values of P that represents the maximum temperature increase on the transformer windings.

From Fig. 14, it is very concerning that the transformer hottest winding transformer becomes very high even for the lowest value of P considered (0.5). The temperature even goes extremely high from 2.00 pm to 6.00 pm. Therefore, the consumers should be very careful in energy consumption during that period.

C.2) The hottest spot temperature, top oil temperature and percentage loss of life of distribution transformer considering harmonics' presence in load current

As discussed in [12], the FHL and FHL-STR values do not change, as the harmonic frequency component distribution and frequency component of non-sinusoidal current remain the same. Therefore, FHL and FHL-STR values are assumed constant as the load current in this work changes considering the harmonic frequency component remains the same and their relative magnitude changes in proportion to the load current.

TABLE VIII: %LOL OF TRANSFORMER 1 FOR DIFFERENT VALUES OF F_{HL} AND F_{HL-STR} FOR APRIL 2020

P	**%LOL (APRIL)**				
	F_{HL} = 1.0 F_{HL-STR} = 1.0	**F_{HL} = 2.73 F_{HL-STR} =**	**F_{HL} = 3.11 F_{HL-STR} =**	**F_{HL} = 6.48 F_{HL-STR} = 1.38**	**F_{HL} = 8.1 F_{HL-STR} = 1.58**

The hottest spot temperatures of the transformer 1 for the month April, considering F_{HL} = 2.73 and F_{HL-STR} = 1.14, are shown in Fig. 14 which indicate that the hottest spot temperature exceeds 200°C for P=0.5 and above whereas the temperature exceeds 200°C for P=0.6 and above for non-harmonic condition (Fig. 10). Similarly, for higher values of F_{HL} and F_{HL-STR}, the temperature exceeds 200°C for lower values of P which is evident from TABLE VIII.

		1.14	1.19		
0.5	0.021	0.117	0.168	2.52	7.73
0.6	0.517	3.39	5.00	3.6760	NA
0.7	9.62	NA	NA	NA	NA
0.75	37.00	NA	NA	NA	NA
0.8	NA	NA	NA	NA	NA
0.9	NA	NA	NA	NA	NA
1.0	NA	NA	NA	NA	NA
1.1	NA	NA	NA	NA	NA
1.2	NA	NA	NA	NA	NA
1.3	NA	NA	NA	NA	NA
1.4	NA	NA	NA	NA	NA
1.5	NA	NA	NA	NA	NA

TABLE VIII represents the percentage loss of life (%LOL) of transformer 1 for different values of F_{HL} and F_{HL-STR} for the month of April in 2020 for all values of P. It is evident from the TABLE VIII that, for the month of April the %LOL of transformer gets extremely high. For higher values of F_{HL} and $F_{HL-STR,}$ less values of P keep the transformer %LOL less than 50%. The not applicable (NA) condition in TABLE VIII indicates that for corresponding P, F_{HL} and F_{HL-STR}, %LOL goes above 50%. The different values of F_{HL} and F_{HL-STR} considered in this work are taken from [5].

TABLE IX: %LOL OF TRANSFORMER 1 FOR DIFFERENT VALUES OF F_{HL} AND F_{HL-STR} FOR APRIL 2020

P	%LOL (APRIL)				
	F_{HL} = 1.0 F_{HL-STR} = 1.0	F_{HL} = 2.73 F_{HL-STR} = 1.14	F_{HL} = 3.11 F_{HL-STR} = 1.19	F_{HL} = 6.48 F_{HL-STR} = 1.38	F_{HL} = 8.1 F_{HL-STR} = 1.58
0.5	NA	NA	NA	NA	NA
0.6	NA	NA	NA	NA	NA
0.7	NA	NA	NA	NA	NA
0.75	NA	NA	NA	NA	NA
0.8	NA	NA	NA	NA	NA
0.9	NA	NA	NA	NA	NA
1.0	NA	NA	NA	NA	NA
1.1	NA	NA	NA	NA	NA
1.2	NA	NA	NA	NA	NA
1.3	NA	NA	NA	NA	NA
1.4	NA	NA	NA	NA	NA
1.5	NA	NA	NA	NA	NA

TABLE IX represents the transformer loss of life considering the current for maximum demands tabulated in TABLE VII. It is a matter of concern that, for the chosen values of P, there is no incident found where the transformer loss of life is 50% or lesser. Therefore, higher consumption during the COVID-19 pandemic lockdown period can seriously damage the residential distribution transformer if these energy demands continue for longer times.

IV. MITIGATION OF ADVERSE EFFECTS OF INCREASED ENERGY CONSUMPTION ON DISTRIBUTION TRANSFORMER

In this work, in order to mitigate the adverse effects of increased energy consumptions at houses on distribution transformers, three types of solutions are proposed. First, the operation of the BTM sources such as the PV power, battery energy storage, and electric vehicle during office hours are considered. It is expected that the BTM sources will meet the increased amount of energy consumptions so that loads on distribution transformers decrease and also the percentage loss of life (%LOL) of the residential transformers gets reduced.

The second solution proposed is to schedule 10% loads from 1.00 pm to 5.00 pm for later hours, as the hottest spot temperature of transformer winding rises high during this time period.

The third solution can be intelligently using loads having less harmonic distortion factor during the scheduling time proposed in the second solution so that the harmonic loss factor becomes less for current provided by the transformer which will in fact reduce the hottest spot temperature rise of transformer winding and reduce the percentage loss of life.

These three solutions are described in details below.

A. Providing Increased Energy Consumption by BTM Sources

In this case, it is considered that the grid will provide power at houses as usual, however, the PV system will be able to provide most of the increased amount of energy consumptions during office hours. Moreover, since residents are assumed to be staying at homes, their electric vehicles can be used as a power source during the period from 9 am to 6 pm. Here it is considered that the apartments have a central battery storage of 9 kWh which will be charged by the excess day time PV power. The electric vehicles will be charged during nighttime only by the battery energy storage. It is assumed that the building has one electric vehicle having battery rating as 4.4 kWh [16] and that can be used from 70% to 90% of the battery capacity.

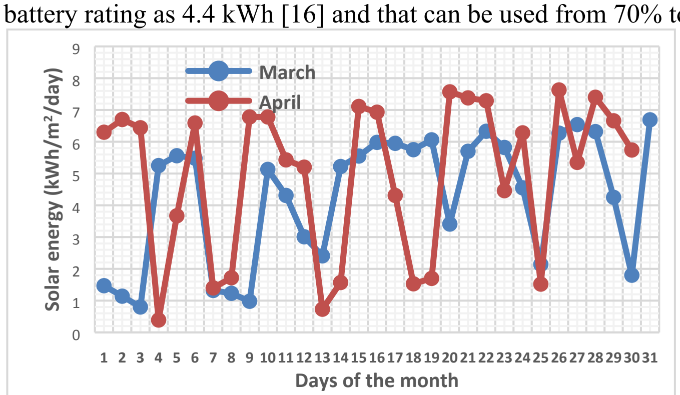


Fig. 15. Total solar energy available per day for March and April 2020.

The available total solar energy for the month of March and April in 2020 are shown in Fig. 15 [13]-[14]. From the data in Fig. 15, after calculation, the average solar energy per day appeared to be 4.27 kWh/m^2/day and 4.95 kWh/m^2/day, which means a solar cell having dimension of 1 m^2 will produce 4.27 kWh/day and 4.95 kWh/day, for the month of March and April, respectively. However, the lengths of days are not equal for the month of March and the office hour is only considered in this work. Hence, it is assumed that during the time from 9am to 6 pm 80% and 70% of total energy is available, for the month of March and April, respectively. Therefore, for 9 hours, the total available energy will be 3.416 kWh/m^2 and 3.465 kWh/m^2 which give the average solar energy of 0.1897 kWh/m^2 and 0.1925 kWh/m^2 available for every half an hour for the month of March and April, respectively, in 2020.

TABLE X: PER UNIT CURRENT OF RESIDENTIAL TRANSFORMER 1 FOR THE MONTH OF APRIL 2020 (BASED ON CONSUMER 1)

Time	P											
	.5	.6	.7	.75	.8	.9	1	1.1	1.2	1.3	1.4	1.5
9:00 AM	0.000	0.000	0.000	0.000	0.002	0.063	0.124	0.185	0.245	0.306	0.367	0.428
9:30 AM	0.000	0.000	0.001	0.035	0.070	0.139	0.208	0.277	0.347	0.416	0.485	0.554
10:00 AM	0.000	0.024	0.109	0.151	0.194	0.278	0.363	0.448	0.532	0.617	0.702	0.787
10:30 AM	0.000	0.000	0.057	0.095	0.134	0.211	0.289	0.366	0.443	0.520	0.598	0.675
11:00 AM	0.000	0.045	0.134	0.178	0.222	0.310	0.398	0.487	0.575	0.663	0.751	0.840
11:30 AM	0.006	0.104	0.202	0.251	0.300	0.398	0.496	0.594	0.692	0.791	0.889	0.987
12:00 PM	0.000	0.000	0.000	0.000	0.000	0.033	0.091	0.148	0.205	0.263	0.320	0.378
12:30 PM	0.000	0.000	0.000	0.003	0.035	0.100	0.165	0.230	0.295	0.360	0.425	0.490
1:00 PM	0.000	0.020	0.103	0.145	0.187	0.271	0.355	0.439	0.523	0.607	0.691	0.775
1:30 PM	0.000	0.070	0.162	0.209	0.255	0.347	0.440	0.532	0.624	0.717	0.809	0.901
2:00 PM	0.274	0.425	0.577	0.653	0.729	0.880	1.032	1.183	1.335	1.486	1.638	1.790
2:30 PM	0.532	0.735	0.938	1.040	1.141	1.344	1.547	1.751	1.954	2.157	2.360	2.563
3:00 PM	0.640	0.864	1.089	1.201	1.314	1.538	1.763	1.988	2.212	2.437	2.662	2.887
3:30 PM	0.345	0.511	0.677	0.760	0.843	1.009	1.175	1.341	1.507	1.672	1.838	2.004
4:00 PM	0.104	0.222	0.340	0.398	0.457	0.575	0.692	0.810	0.928	1.045	1.163	1.281
4:30 PM	0.270	0.421	0.571	0.647	0.722	0.873	1.024	1.175	1.325	1.476	1.627	1.778
5:00 PM	0.145	0.271	0.397	0.460	0.523	0.649	0.775	0.901	1.027	1.152	1.278	1.404
5:30 PM	0.182	0.315	0.448	0.515	0.581	0.714	0.847	0.981	1.114	1.247	1.380	1.513
6:00 PM	0.500	0.697	0.894	0.992	1.091	1.288	1.485	1.681	1.878	2.075	2.272	2.469

For the consumer 1, the average energy consumption rise in April is 0.0499 kWh for every half an hour (see TABLE I). Therefore, in the six apartments that are under the transformer 1, will have an average increase in energy consumption of 0.2996 kWh for every half an hour (considering the P value to be 1). The average solar panel of dimension is 5.4 feet by 3.25 feet which is 1.63 m^2. As 0.1925 kWh/m^2 average energy is available for every half an hour for the month of April in 2020, if the solar panel of above dimension is installed in the building, it will have 0.3138 kWh average of energy for every half an hour available at the sonar panel. Considering 25% efficiency, each panel will produce 0.07845 kWh energy for every half an hour. Therefore, four panels will produce 0.3138 kWh average of energy for each half an hour for the month of April which is slightly higher than the average energy increase (0.2996 kWh). This fact indicates that the proposed PV system can meet the increased energy consumption demand for consumer 1 in April 2020.

B. Mitigation of Effects of Increased Transformer Temperature and Percentage Loss of Life by BTM sources

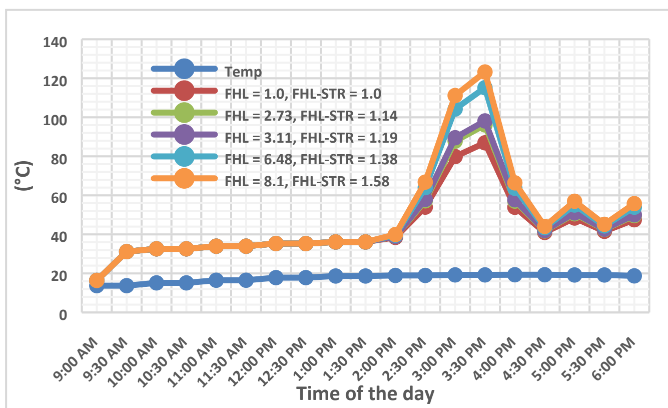


Fig. 16. Hottest spot temperature of transformer 1 winding in April for P=.5 for April 2020.

The transformer per unit current, T_{iBTM} after considering the BTM sources, is calculated by the following equation:

$$T_{iBTM-pu} = \begin{cases} \dfrac{I_{c,h} \times n \times P - I_{BTM}}{I_{Trated}} \; if \; I_{c,h} \times n \times P > I_{BTM} \\ 0 \quad\quad if \quad I_{c,h} \times n \times P < I_{BTM} \end{cases} \quad (19)$$

Where, $I_{c,h}$, n, P and I_{Trated} are the same as in equation (1). I_{BTM} is the current that is provided by the BTM sources during the office hour of the COVID period. It is assumed that the battery energy storage will be charged by the extra current if the first numerator of equation (19) gets lower than I_{BTM} and transformer neither gives nor receives the extra power from the BTM sources. Moreover, I_{BTM} is calculated from the following equation:

$$I_{BTM} = \frac{E_{BTM} \times 1000}{0.5 \times 120} \quad (20)$$

Where, E_{BTM} is the energy available (0.3630 kWh) for each half an hour by the PV and electric vehicle.

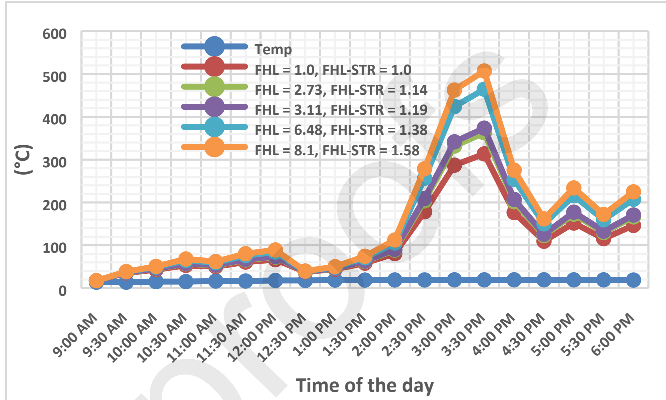


Fig. 17. Hottest spot temperature of transformer 1 winding in April for P=1 for April 2020.

Furthermore, for the considered case of the proposed PV source and electric vehicle during office hours, the per unit current of the transformer for consumer 1 for different values of P are calculated using (19) and shown in TABLE X. It is noticed that the per unit current values are less than the demand on the transformer when all the power is supplied by the transformer (see TABLE VI). For example, in April 2020, at 9.00 am the $I_{c,h}$ is 1.266 A (TABLE II). However, I_{BTM} value is calculated to be 6.05 A using (20) and neglecting the power loss to convert dc currents into ac currents. The first numerator value is 3.798 A (considering P=0.5) which is less than 6.05 A. Therefore, the current provided by the transformer would be 0 A (TABLE X, 9.00 am, P=0.5). However, for the same time and current, the first numerator becomes 7.596 A considering P=1 which is higher than 6.05 A. Therefore, the current provided by the transformer would be 1.546 A. Considering the transformer rated current to be 12.5 A, the per unit current would be 0.124 (TABLE X, 9.00 am, P=1).

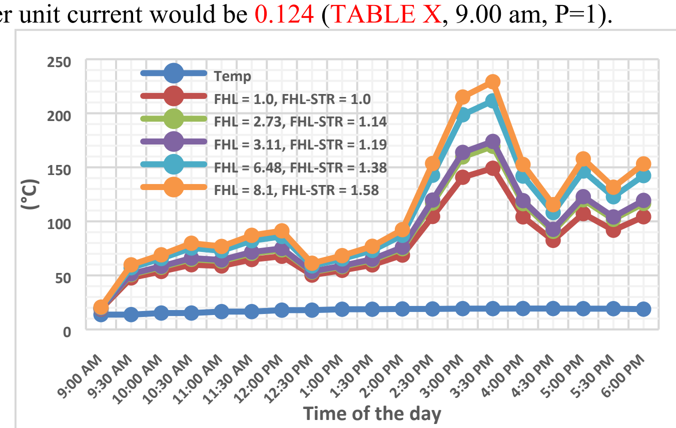


Fig. 18. Hottest spot temperature of transformer 1 winding in April for P=.5 for April 2020.

The hottest spot temperature of the transformer winding for the month of April, for the considered case, are shown in Fig. 16 for P values of 0.5. Due to power provision by PV source, battery storage and electric vehicle, the hottest winding temperature never crosses 200 °C for case 1 for P=0.5 for all F_{HL} and $F_{HL\text{-}STR}$ values. Moreover, for F_{HL} = 2.73 and $F_{HL\text{-}STR}$ = 1.14, the maximum hottest spot temperature remained under 100 °C where the temperature exceeds above 170 °C for the same F_{HL} and $F_{HL\text{-}STR}$ values as shown in Fig. 10.

Moreover, as shown in Fig. 17, in case of P=1 the hottest spot temperature of transformer winding exceeds 200 °C for half an hour (3.00-3.30 pm). However, for F_{HL} = 2.73 and $F_{HL\text{-}STR}$ = 1.14, the hottest spot temperature exceeds just above 300 °C due to provision of power by PV, battery storage and hybrid electric vehicle. However, the hottest winding temperature exceeds 500 °C for the same F_{HL} and $F_{HL\text{-}STR}$ values as shown in Fig. 14. The same situation happens for all other increased F_{HL} and $F_{HL\text{-}STR}$ values which increase the %LOL of the transformer.

TABLE XI: %LOL OF TRANSFORMER FOR CASE 1 FOR APRIL 2020

P	%LOL (April)	
	Without mitigation solution (F_{HL} = 2.73, $F_{HL\text{-}STR}$ = 1.14)	With proposed mitigation solution (F_{HL} = 2.73, $F_{HL\text{-}STR}$ = 1.14)
0.5	0.117	2.16E-05
0.6	3.39	1.06E-03
0.7	NA	4.60E-02
0.75	NA	2.72E-01
0.8	NA	1.47
0.9	NA	32.6
1.0	NA	7.41
1.1	NA	NA
1.2	NA	NA
1.3	NA	NA
1.4	NA	NA
1.5	NA	NA

The percentage loss of life, with and without mitigation solution by the BTM sources, is shown in TABLE XI for F_{HL} = 2.73 and $F_{HL\text{-}STR}$ = 1.14. From TABLE XI, it is clear that, for the considered case, up to 0.9 value of P can keep transformer loss of life (%LOL) below 50%. For normal operation without considering the proposed BTM solution, the %LOL goes beyond 50% for P=0.6. Therefore, inclusion of the BTM sources and energy storage certainly increase the operation range of load and decrease the %LOL for the same value of load.

C. Mitigation of Effects of Increased Transformer Temperature and Percentage Loss of Life by Load Scheduling

As previously described, the lock down situation increases the energy consumption which in turn increases the hottest spot temperature of transformer winding, top oil temperature specially from 1.00 pm to 4.00 pm. Therefore, if the consumers can shift some of the loads of that period for later time or night time, it will decrease the temperature rise in the winding and oil and the percentage loss of transformer's life will be reduced. This shifting of loads can be easily facilitated by shifting all the cooking, washing clothes, dishes, etc., for night time or later hours, lowering the temperature setting to slightly lower value to the consumers' utmost liking.

In this case, only 10% of loads that are consumed on average during 1.00 pm to 4.00 pm are assumed to be shifted or scheduled for later hours or night time.

The currents for this case are similar to what are tabulated in TABLE II except for the fact that only the average currents shown in TABLE II will be reduced 10% from 1.00 pm to 4.00 pm. This is also true for per unit currents shown in TABLE VI for all values of P. Based on this calculation of currents, the hottest spot temperature of transformer winding for P value of 0.5 and 1.0 are shown in Fig. 18 and Fig. 19, respectively for consumer 1.

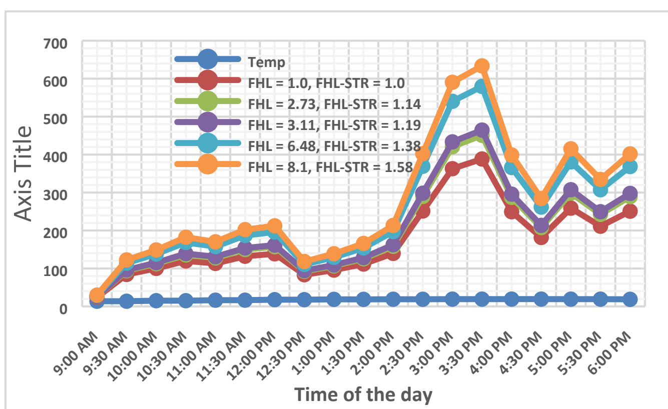


Fig. 19. Hottest spot temperature of transformer 1 winding in April for P=1 for April 2020.

TABLE XII: %LOL OF TRANSFORMER FOR CASE 1 FOR APRIL 2020

P	%LOL (April)	
	Without mitigation solution (F_{HL} = 2.73, $F_{HL\text{-}STR}$ = 1.14)	With proposed mitigation solution (F_{HL} = 2.73, $F_{HL\text{-}STR}$ = 1.14)

0.5	0.117	1.94E-02
0.6	3.39	4.73E-01
0.7	NA	8.73
0.75	NA	33.5
0.8	NA	NA
0.9	NA	NA
1.0	NA	NA
1.1	NA	NA
1.2	NA	NA
1.3	NA	NA
1.4	NA	NA
1.5	NA	NA

From Fig. 18 and Fig. 19, it can be concluded that the temperature rise reduction in this case will be less than that of the proposed solution (BTM sources) in the previous section, but it is effective in reducing temperature rise. However, it increases the range of P values for which the percentage loss of life will be less than 50% as shown in TABLE XII. Moreover, the temperature rise, and percentage loss of life can be further reduced if the consumers are willing to schedule more loads for later hours.

D. Mitigation of Effects of Increased Transformer Temperature and Percentage Loss of Life by Load Scheduling and Utilizing Loads Causing Less Harmonic Distortion

There are two types of loads (i.e. ac and dc) that are used in the residential buildings. Among them, television, mobile phone, water purifier, microwave oven, washing machine, etc. are dc loads that produce higher harmonic contents in current when taking power from the system [17]. Among the ac loads, fluorescent lamp/tube, fan with electronic regulator, air conditioner, etc., produce higher harmonics. These harmonic contents can produce excessive heating for the transformer.

Therefore, along with the load scheduling proposed in the previous subsection, the loads can be used such a way that the loads that produce higher harmonics will be limitedly used from 1.00 pm to 4.00 pm. This will help reduce the harmonic loss factor and harmonic loss factor for the stray losses, and thus the temperature rise and percentage loss of life can be reduced further. In this case, it is assumed that the load scheduling is done in such a way the harmonic loss factor and harmonic loss factor for the stray losses are decreased by 5% from the considered value for the normal operating conditions.

The new harmonic loss factors and harmonic loss factor for the stray losses, after considering 5% reduction, are shown in Fig. 20 and Fig. 21.

TABLE XIII: %LOL OF TRANSFORMER FOR CASE 1 FOR APRIL 2020

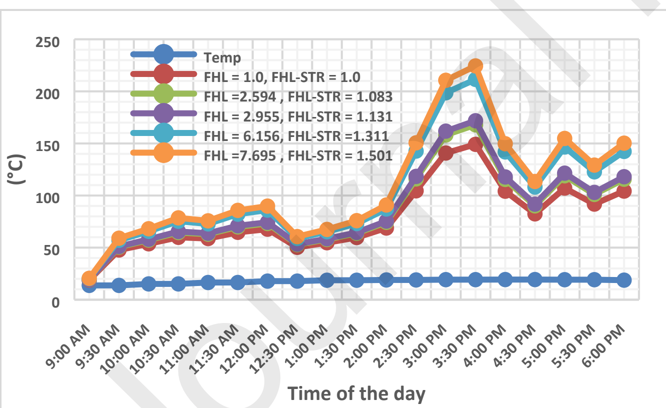


Fig. 20. Hottest spot temperature of transformer 1 winding in April for P=.5 for April 2020.

	%LOL (April)	
	Without mitigation solution (F_{HL} = 2.73, $F_{HL\text{-}STR}$ = 1.14)	With proposed mitigation solution (F_{HL} = 2.594, $F_{HL\text{-}STR}$ = 1.083)
0.5	0.117	1.72E-02
0.6	3.39	4.14E-01
0.7	NA	7.59
0.75	NA	29.1
0.8	NA	NA
0.9	NA	NA
1.0	NA	NA
1.1	NA	NA

1.2	NA	NA
1.3	NA	NA
1.4	NA	NA
1.5	NA	NA

Fig. 20 and Fig. 21 represent the hottest spot temperature of transformer winding for P value of 0.5 and 1.0, respectively. It is evident from these two figures that the temperature reduces further as compared to Fig. 18 and Fig. 19, respectively, due to considered reduction of harmonic loss factor and harmonic loss factor for other stray losses. From TABLE XIII, it is evident that the percentage loss of life reduces for this case as compared to the case considered in the previous subsection (see TABLE XII) for all values of P ranging from 0.5 to 0.75.

V. Conclusion

This paper analyzes the impact of COVID-19 pandemic situation on residential loads and local distribution transformer. Six types of consumers having different consumption patterns are considered. Based on the analysis, the following conclusions can be made:

1) Due to the lockdown situation, the energy consumptions of consumers have increased during the entire office hour or part of the office hour.

2) The residential transformer gets vulnerable as the value of P gets higher. Also, with higher harmonic loss factor, the range of P values for which the transformer can operate safely, decreases.

3) The proposed BTM sources, load scheduling without or with considering limited use of loads that produce higher harmonic contents in currents, are effective during this lockdown conditions as it increases the range of P values for safe operating condition of residential transformer and reduces the %LOL for all P values as compared to the situation without mitigation solutions.

In our future work, other new solutions to mitigate the adverse effects of increased energy consumptions on distribution transformers will be explored. Moreover, if the COVID 19 situation continues for a long time, much more data for varied consumers will be analyzed.

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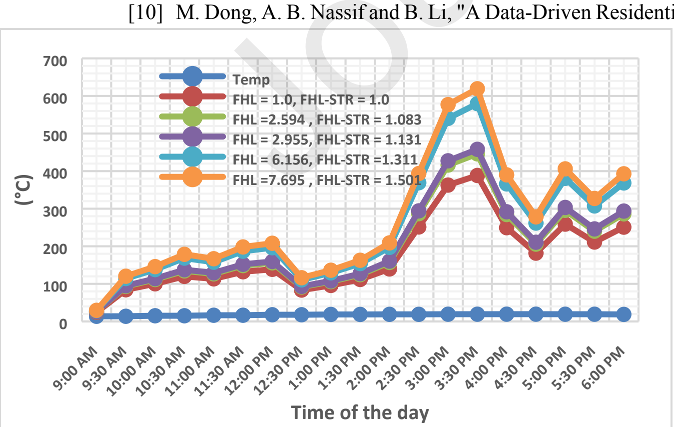

Fig. 21. Hottest spot temperature of transformer 1 winding in April for P=1 for April 2020.

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