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Impact of uncoordinated and coordinated charging of plug-in electric vehicles on substation transformer

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ABSTRACT

With the rapidly growing interest in smart grid technology, plug-in electric vehicles (PEVs) are expected to become more popular as low emission replacement for the petroleum based vehicles. Significant PEVs charging activities will mostly take place in customer's premises, public or corporate car parks and electric charging stations. Therefore, utilities are concern about the possible detrimental impacts of these sizeable and unpredictable loads on the performance of distribution grids. Based on a recently proposed real-time smart load management (RT-SLM) control strategy, this paper focuses on the impact of uncoordinated and coordinated PEVs charging on substation transformer loading, system losses and voltage profile. Detailed simulations are performed on a 449 node smart grid system consisting of the modified IEEE 23 kV distribution system serving 4 charging stations and 22 low voltage residential networks populated with PEVs.

Introduction

SMART grids and their sophisticated two-way communication infrastructure, smart meters and sensors will enable effective coordination and usage of available energy resources through real-time monitoring and control of transmission, distribution and end-user consumer assets such as plug-in electric vehicles (PEVs) and smart appliances [1-2]. PEVs are expected to gain popularity over conventional fuel-based vehicles. However, the PEVs battery charging requirements will need to be fulfilled by new electric vehicle infrastructure to be supported by the rollout of smart grids. Significant PEVs charging activities will mostly take place in customer's premises, public or corporate car parks and electric charging stations.

Therefore, utilities are concern about the possible detrimental impacts of these sizeable and unpredictable loads on the performance of distribution grids. From the utilities perspectives, operation of PEVs in smart grid is a demand side management (DSM) problem since PEV battery chargers and PEV charging stations represent sizeable loads [3-7]. Uncoordinated and random PEV charging activities could significantly stress the distribution system causing severe voltage fluctuations, suboptimal generation dispatch, degraded system efficiency and economy [3-4]. Fortunately, the development of smart grid communication infrastructure will provide the opportunity to manage this problem with real-time intelligent coordinated charging of PEVs [3].

Some recent publications have studied the integration of customer DSM for demand response and load control of smart grids to improve the system load profile and to reduce the peak demand [3-7]. To achieve this, many countries are developing technologies such as smart metering and smart appliances [8-9]. PEVs can also be utilized to support smart grids by performing ancillary services such as frequency regulation and energy storage. Reference [10] makes efficient use of the distributed power of electric vehicles and develops an optimal vehicle-to-grid (V2G) aggregator for frequency regulation.

This paper utilizes a recently proposed real-time smart load management (RT-SLM) control strategy [4] to investigate the stress on substation transformer, system losses and voltage profile of smart grids with the integration of charging stations and PEV charging activities.

The employed sensitivities-based RT-SLM [4] allocates PEVs for charging as soon as possible based on real-time (e.g., every 5 minutes) cost minimization and improves the voltage profile while considering designated charging time zone priorities specified by PEVs owners.

To explore the performance of the substation transformer and the improvements in smart grid performance, RT-SLM is simulated with a detailed 449 node smart grid topology that is consisting of a high voltage (HV) distribution system feeding 4 charging stations and 22 integrated low voltage (LV) residential networks populated with PEVs.

Simulation results are presented for coordinated and uncoordinated charging with PEVs penetration levels of 16%, 32%, 47% and 63% considering three designated time zones; red: 1800h-2200h, blue: 2200h-0100h, and green: 0100h-0800h.

RT-SLM for Coordinated PEV Charging

Details of the RT-SLM for PEV charging coordination are available in reference [4]. This section provides a short overview of the proposed approach.

The problem is formulated into an objective function that is to minimize the total system losses along with series of system constraints (to regulate node voltages and set a ceiling limit for the total maximum system demand)

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Coordinated PEV Charging Constraints

The voltage limits are set to ± 10%:

$$V^{\min} \le V_k \le V^{\max} \quad \text{for } k = 1,..., n. \qquad (1)$$

where $V^{\min} = 0.9\,pu$, $V^{\max} = 1.1\,pu$, k and n are the node number and total number of nodes, respectively.

To prevent overload conditions caused by PEV charging, a ceiling limit is also considered for total maximum system demand:

$$P_{\Delta t}^{\text{total demand}} = \sum_k P_{\Delta t,k}^{load} \le D_{\Delta t,\max} \qquad (2)$$

where $P_{\Delta t}^{\text{total demand}}$ is the total power consumption at time interval Δt within the 24 hours, $P_{\Delta t,k}^{load}$ is the power consumption of node k at Δt and $D_{\Delta t,max}$ is maximum demand level at Δt that would normally occur without any PEVs.

Coordinated PEV Charging Objective Function

The selected objective function for the PEV charging coordination problem is the minimization of system demand and total system power losses over 24 hours:

$$\min F = F_{Demand} + F_{Loss}$$

$$= \min \sum_{h=h_{start}}^{h_{end}} Demand^{\,h} + \min\ W_{loss} = \qquad (3)$$

$$= \min \sum_{h=h_{start}}^{h_{end}} \sum_{k=1}^{n} P_{k,load}^{h} + \min \sum_{h=1}^{24} P_{loss}^{h}$$

where h_{start} and h_{end} correspond to the starting and ending charging times within the selected charging time zone, respectively and $P_{k,load}^{h}$ is the load demand of node k at time step h. Based on Newton-based power flow outputs, the power losses of the distribution system are computed from line losses in sections between nodes k and k+1 is

$$P_{loss(k,k+1)} = R_{k,k+1}\left(\left|V_{k,k+1} - V_k\right| \left|y_{k,k+1}\right|\right)^2 \qquad (4)$$

and the total power loss is

$$P_{loss} = \sum_{k=0}^{n-1} P_{loss(k,k+1)} \qquad (5)$$

Real-Time Coordinated PEV Charging Algorithm

With the random plugging of PEVs at residential nodes, the proposed RT-SLM coordination algorithm of [4] will charge the vehicles as soon as possible based on their designated priorities (Fig. 1). Three PEV charging zones are considered as shown in Fig. 2:

- Red charging zone (1800h-2200h)- coinciding with on-peak period and is designated for (high priority) PEV owners wanting to charge their PEVs as soon as possible.
- Blue charging zone (2200h-0100h)- is for (medium priority) consumers that prefer to charge their vehicles at partially off-peak periods.
- Green charging zone (0100h-0800h)- is the period that most PEV charging will take place since most (low priority) consumers will require their vehicles fully charged for use throughout the next day.

The proposed RT-SLM shown in Fig. 1 utilizes the maximum sensitivity selections (MSS) optimization approach to update the status of PEVs every 15 minutes, determine the near-optimal coordination pattern and signal the vehicles to start charging at the most appropriate times based on their locations, their designated charging time zones and grid generation level such that system losses during the optimization time interval are minimized and bus voltages are regulated. RT-SLM coordination algorithm starts with the highest priority group of PEVs (i.e. red) and through scanning a predetermined system load curve (Fig. 2), finds the ideal time to schedule PEV which corresponds to minimum system losses and minimum system demand (Eq. 3). The order of vehicle charging is selected based on the maximum sensitivity selections (MSS) of buses such that within each priority group the PEVs with the least impact on power losses and system voltage profile (as computed from load flow) are quickly charged. PEV nodes resulting in violations of constraints (Eqs. 1-2) will be rescheduled until the constraints are satisfied. This process is repeated at each time interval until all PEVs are properly scheduled.

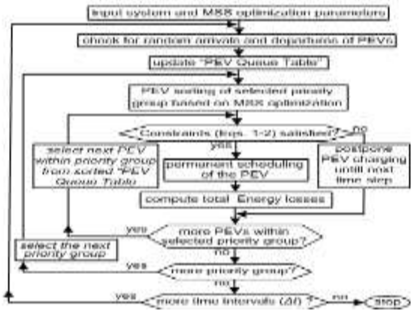

Fig. 1. Proposed RT-SLM algorithm for coordinated PEV charging [4]

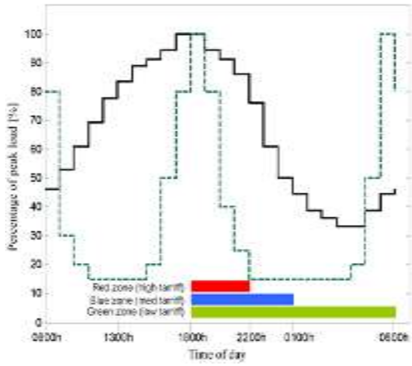

Fig. 2. Daily load curves for residential loads and charging stations.

The Simulated Smart Grid Test System With Pevs And Charging Stations

In order to explore the impact of charging stations and multiple domestic PEV charging on the performance of substation transformer in smart grids, simulation studies with uncoordinated (random) and coordinated PEVs charging have been performed on the 449 node smart grid distribution system shown in Fig. 3. The system consists of the IEEE 31 node 23 kV system, 4 PEV charging stations and 22 low voltage 415V residential feeders. Each LV residential feeder has 19 nodes representing customer households with varying penetrations of PEVs.

System Topology

The selected system is a modification of the IEEE 31 bus 23 kV distribution test system [11] combined with 22 residential LV 415 V networks. Each LV feeder consists of 19 nodes representing customer households with selected nodes assigned PEVs, priority and charging zone [4]. The residential feeders are supplied from the HV main buses via 23kV/415V 100 kVA distribution transformers. The total number of nodes is 449 (31 HV nodes and 418 LV nodes). System data are listed in [4].

5.Residential Load Profiles

Based on actual recordings from a distribution transformer in Western Australia, residential load curves as shown in Fig. 2 are constructed to model the domestic load variations (without PEV charging) at each house. A power factor of 0.9 is assumed with an average house peak demand of 2 kW.

6.PEVs Charging Profile and Battery Ratings

PEV charger load profiles are constructed assuming each battery has a maximum storage capacity of 10 kWh [9] and only 70% of the battery capacity is used to optimise its expected life expectancy. Assuming 88% charging efficiency, each PEV requires 8 kWh of energy from the utility grid for its battery to be fully charged. In this paper, the battery chargers for PEV are rated at 4 kW at unity power factor since most residential circuits can support 15-20 Amps which can deliver 4.6 kW for a standard single phase 230 V supply.

7.PEV Penetrations and Priority Charging Time Zones

Four PEV penetration levels of 17%, 31%, 46% and 62% are simulated. For each penetration, PEVs are grouped into red (1800h-2200h); blue (2200h-0100h) and green (0100h-0800h) charging time zones corresponding to high, medium and low priority residential consumers (Fig. 2).

8.PEV Charging Stations

The impact of rapid PEV charging stations is considered at four sites near the residential areas located at HV main buses 4, 7, 9 and 11. It is assumed that the charging stations follow the load curve shown in Fig. 2 with two load peaks corresponding to PEV owners charging their vehicles before they go to work in the morning and after work in the evening. The maximum peak demand of PEV charging stations corresponds to the maximum number of PEVs that can pull into a charging station during its busiest time which is assumed to be 6 PEVs on average. The PEV charging station power requirement for the rapid charging of one PEV is assumed to be approximately 14.4 kW at unity power factor. Therefore, the peak demand of one charging station is 86.4 kW.

9.Distribution and Substation Transformers

The focuses of this paper is the 132kV/23kV substation transformers connected between nodes 1 and 2 (Fig. 3) supplying the distribution and residential networks. This transformer is rated at 10 MVA with a reactance of 0.04Ω.

There are also twenty two 100kVA, 23kV/415V distribution transformers (DT-10 to DT-31) supplying the low voltage residential networks with a reactance of 0.0654Ω. The system and transformer data are listed in [4].

Fig. 3. (a) The 449 node smart grid distribution system topology and (b) Detailed residential network

RT-SLM coordination results

Simulations are performed considering various PEV charging scenarios as shown in Table I for the smart grid system of Fig. 3. Extensive simulations are performed for uncoordinated and RT-SLM coordinated PEV charging scenarios with a time step of Δt =5 minutes considering PEV penetrations of 17%, 31%,46% and 62%. Due to page limitation, the system demand, voltage profile, total power losses and distribution transformer loading are only plotted for each scenario as shown in Fig.4 through Fig. 7.

Discussion

Simulation results with PEV penetration levels of 16%, 32%, 47% and 63% based on uncoordinated (Figs. 4-5) and real-time coordinated (Fig. 6-7) charging schemes for the smart grid system of Fig. 3 with 4 charging stations are respectively summarized in Tables II, III and IV.

Cases A1: Uncoordinated PEV charging is investigated by simulating a normal distribution of PEV charging loads with penetration levels of 16%, 32%, 47% and 63% occurring within 1800h-0800h (Case A1, Fig. 4, rows 4-8 of Table II), and 1800h-2200h (Case A2, Fig. 5, rows 8-13 of Table II). Even with the unlikely random charging scenario of Case A1 where the PEV charging are assumed to be uniformly distributed overnight (1800h-0800h), the power demand and required generation show significant increases during the peak hours as shown in Fig. 4 (a).

Case A2: This is a more realistic scenario where the PEV owners start charging their vehicles as soon as they get home during the early evening hours (1800h-0800h). as a consequence the system peak rises sharply and broadens due to the significant PEV charging activities as can be shown in Fig. 5 (a). Furthermore, substation transformer current increases very rapidly (Fig. 6(d) and Table II (rows 8-13)).

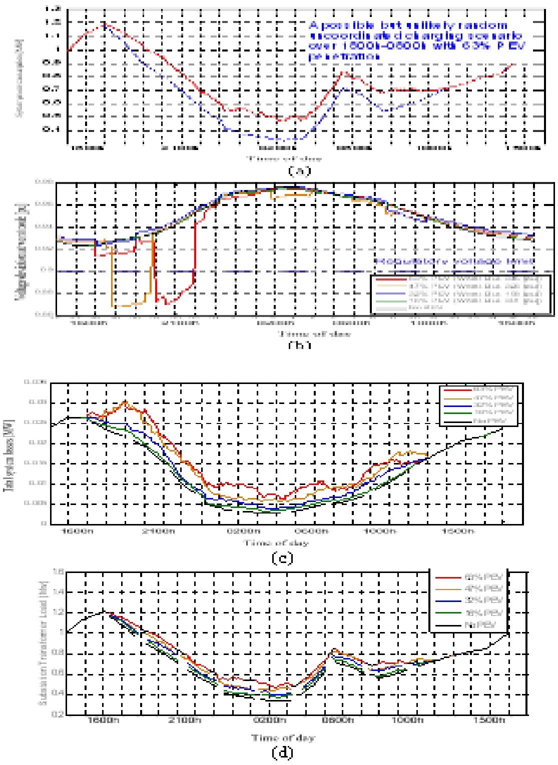

Fig. 4. Case A1: Impact of random uncoordinated PEV charging (63% penetration) within 1800h-0800h on (a) system demand, (b) voltage profile (shown for the worst affected nodes), (c) total system power losses, and (d) distribution transformer loading.

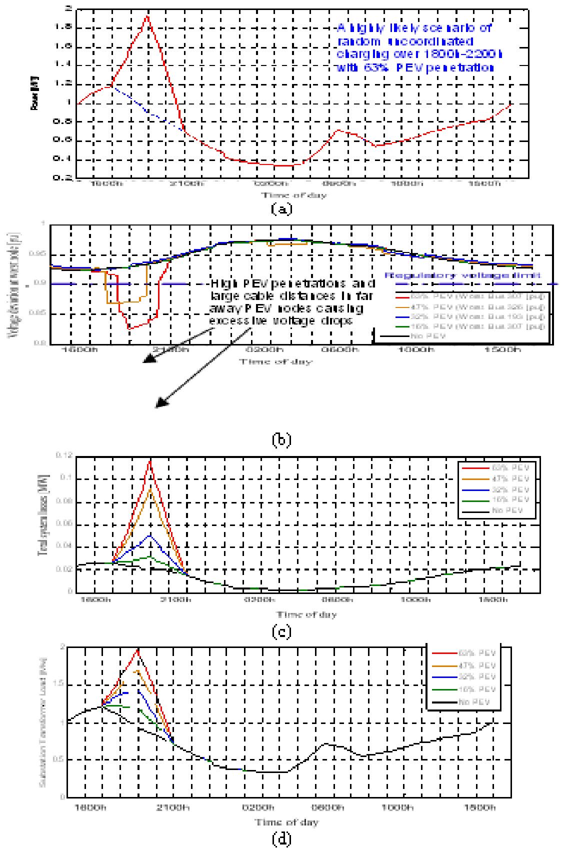

Fig. 5. Case A2: Impact of random uncoordinated PEV charging (63% penetration) within 1800h-2200h on (a) system demand, (b) voltage profile (shown for the worst affected nodes), (c) total system power losses, and (d) distribution transformer loading.

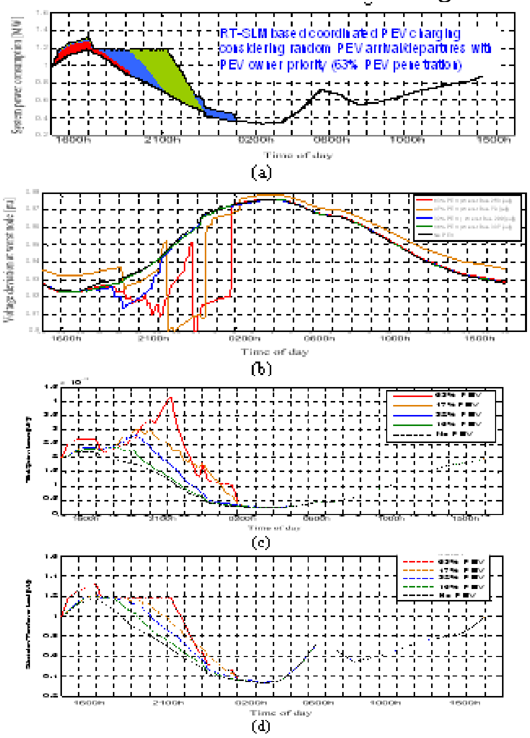

Fig. 6. Case B: Impact of MSS-based RT-SLM coordinated PEV charging (63% penetration) on (a) system demand, (b) voltage profile (shown for the worst affected nodes), (c) total system power losses, and (d) distribution transformer loading.

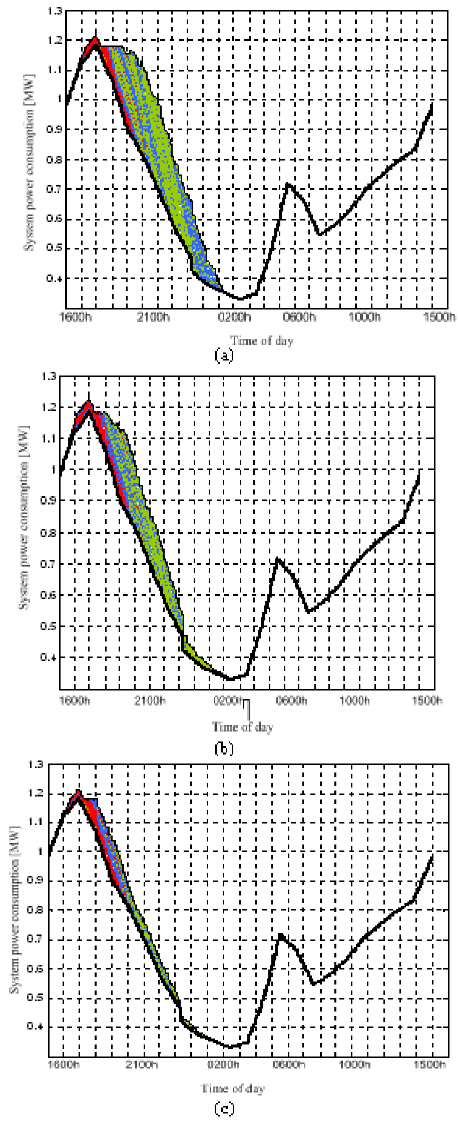

Fig. 7. Case B: System demand with MSS-based RT-SLM coordinated PEV charging for PEV penetration levels of (a) 47%, (b) 32%, (c) 16%.

Case B: The RT-SLM control strategy can successfully handle PEV scheduling while considering consumer designated priorities by smartly distributing charging activities overnight. Substantial improvements in system performance and reduction in substation transformer stress is observed (Figs. 6-7, Tables II, III and IV. Furthermore, the voltages at all nodes are regulated within limits even under large PEV penetrations. System losses, peak generation and transformer load current (except for the unlikely case of 63% penetration level) have also been reduced.

Conclusion

A recently developed real-time PEV charging coordination strategy is utilized to investigate the performance of smart grid distribution system comprising charging stations and residential networks with low, medium and high PEV penetrations. The coordination real-time algorithm includes PEV owner designated charging priorities, system load leveling, voltage profile and loss minimization functions. In particular, the impacts of PEV load management on smart grid demand, voltage profile, total power losses and substation transformer loading patterns are studied. The main impacts of the real-time PEV coordination charging are as follows:

•Diversifying the PEV charging activities such that severe substation and distribution transformer load surges are minimized.
•Maintaining all bus voltages during the 24 hour within regulatory limits.
•The results are valuable for the understanding of future transformer loading scenarios subject to coordinated PEV charging.
•While the implemented coordination approach is beneficial in overall system load leveling and peak shaving, high PEV penetrations may still result in significant increases in substation and individual distribution transformer loads that may exceed their ratings.

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Table I Pev charging scenarios for smart grid system of fig. 3 with pev charging time zones and daily load curve of fig. 2

Case	Charging Scheme (Δt =5 minutes)	Simulation results
A	Uncoordinated random charging over 1800h-0800h (Case A1), 1800h-2200h (Case A2) for PEV penetration levels of 17%, 31%, 46% and 62%.	Figs. 4-5, Table II (rows 4-13)
B	Coordinated RT-SLM charging with a constant maximum demand level of $D_{\Delta t,max}$=0.84MW considering consumer priorities for PEV penetration levels of 17%, 31%, 46% and 62%.while intentionally allowing the medium and low priority consumers to charge their PEVs at earlier hours if there is enough capacity.	Fig. 6-7, Tables II (rows 14-18), III and IV

Table iiImpact of uncoordinated and coordinated pev charging on the performance of smart grid test system shown in fig. 3

PEV [%]	ΔV [%]	Δ loss* [%]	$I_{DT,MAX}$ ** [%]	$I_{ST,MAX}$ *** [%]
Nominal Case without any PEVs				
0	7.646	0.158	0.146	1
Case A1 (Table I, Uncoordinated): Fig. 4				
16	7.646	1.915	0.181	1.0204
32	7.689	1.982	0.181	1.0204
47	7.689	2.146	0.177	1.0204
63	13.029	2.175	0.194	1.0204
Case A2 (Table I, Uncoordinated): Fig. 5				
16	7.661	1.950	0.178	1.0546
32	9.030	2.105	0.219	1.2174
47	16.212	2.460	0.261	1.4473
63	17.630	2.614	0.306	1.6501
Case B (Table I, Coordinated RT-SLM): Figs. 6-7				
16	7.682	0.161	0.178	1.0264
32	8.655	0.171	0.199	1.0364
47	9.998	0.186	0.213	1.0398
63	9.999	0.194	0.199	1.1150

*) Ratio of system losses over 24 hours compared to total power consumption over 24 hours.
**) Maximum of all distribution transformer load currents over 24 hours.
***) Maximum subsataion transformer load current over 24 hours.

Table III Substation transformer load currents over 24 hourswithCoordinated charging for different pev penetrations

PEV (%)	I_{max} (pu)*	I_{min} (pu)*	I_{avg} (pu)*
0	1.000 (@18:00hrs)	0.2766 (@ 03:30hrs)	0.5808
16	1.0264 (@ 18:00hrs)	0.2746 (@03:30hrs)	0.5891
32	1.0364 (@18:00hrs)	0.2779 (@03:30hrs)	0.6073
47	1.0398 (@18:00hrs)	0.2786 (@03:30hrs)	0.6255
63	1.1150 (@ 21:45hrs)	0.2802 (@ 04:00hrs)	0.6569

*) Load currents given in per-unit of peak transformer loading with no PEVs

TABLE IV VOLTAGE PERFORMANCE OVER 24 HOURS WITH COORDINATED CHARGING FOR DIFFERENT PEV PENETRATIONS

PEV (%)	V_{worst} (pu)	V_{avg} (pu)	Worst Node	Worst Time*
0	0.92354	0.9772	307	18:15hrs
16	0.92318	0.97684	307	18:15hrs
32	0.91345	0.97612	288	19:00hrs
47	0.90001	0.97515	79	19:30hrs
63	0.9	0.9746	250	20:00hrs

*) Time at which worst voltage occurs (to the nearest 15 minute)