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Experimental assessment of UPS battery load model considering harmonics and its investigation in the distribution systems ☆

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Abstract

Uninterruptible Power Supply (UPS) inverter battery systems in the recent years are playing significant role in achieving protection against power interruptions and in improving efficiency and cost effectiveness of the power networks. In this article, an assessment of harmonic load model of battery energy storage system is carried out by a detailed experimentation on *10 kVA* single-phase UPS inverter battery. Experimental results are obtained for fundamental powers drawn by the battery during charging, along with harmonic currents generated at various voltage levels. From the measured values, functional relations between voltage and power (real and reactive) have been developed. Results of experimentation are then integrated with radial distribution systems to investigate the impact of harmonic load model of UPS battery on the distribution network. The proposed method is tested on a radial distribution feeder integrated with UPS battery system. Load flow results of integrated distribution system demonstrate that non-linear load model of UPS battery can cause considerable harmonic distortion in the distribution network and increase power losses.

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*Keywords:*Uninterruptible Power Supply; Battery Energy Storage System; Harmonic distortion; Distribution system.

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1. Introduction

Applications of UPS inverter battery systems have been well recognized for meeting peak load demands and for maintaining network reliability by protecting critical loads against supply disturbances. Furthermore, with increasing penetration of distributed energy resources (DERs), integration of such energy storage systems with the distribution network has also drawn considerable attention for improving overall energy efficiency and economic viability of the system.

In recent years, many studies have been performed on interconnection of UPS inverters with power systems, parallel operation of battery modules and control schemes. Divya and Stergaard have presented present status of battery energy storage technology and their impact on power system operation [1]. A method for optimal sizing and operation of battery energy storage in a small power system has been presented by Mercier using numerical simulations on a load frequency control simulator [2]. Qian has presented high-efficiency Lithium-ion battery energy system to work as interface between the battery pack and ac grid [3]. Parallel operation of UPS battery systems has been another area of investigation in the last decade and many researchers have made significant contributions in developing control algorithms for parallel operation of UPS inverter batteries [4 – 7]. Role of UPS battery energy systems in managing the increasing power consumption in data centres has also been recognized and discussed in very recent publications [8 – 9].

With continuous growth of non-linear load in distribution systems, propagation of harmonic distortions in the power networks has become a critical issue. Studies on UPS inverter batteries have definitively established that such systems generate harmonics as these involve extensive use of power electronic devices, which have non-linear characteristics. Some papers have discussed general power quality issues and the compensation of harmonic distortion in UPS batteries in the last decade [10 – 11]. Although the published work so far on UPS battery energy systems has presented various applications, control schemes and techniques for efficiency improvement, yet there is limited literature on the harmonic modeling of these energy storage systems and their impact on the interconnected distribution systems.

The proposed article is based on a comprehensive experimental work conducted on a single-phase UPS battery to develop its harmonic load model using an advanced Power and Harmonic Analyzer. Experimental results are analysed by requisite mathematical framework to formulate load model of UPS inverter battery considering its harmonic distortions. The developed harmonic load model is further integrated with an IEEE radial distribution system (RDS) to investigate the impact of UPS battery load on the distribution network. Section 2 of this paper elaborates the experimental work and tabulates measurement results. Section 3 develops mathematical framework to integrate experimental results of section 2 with RDS data to investigate the effect of UPS battery load model on the distribution system under study. Results of distribution load flow analysis obtained by incorporating harmonic model of UPS battery are depicted in Section 4, followed by the conclusion of the proposed work in Section 5.

Nomenclature

$[\boldsymbol{I_{Total}}]_{UPS\_battery}$	Total current phasor of UPS battery during charging
$V_{UPS\_battery}$	Voltage applied to UPS battery
$P_{UPS\_battery}$	Real power drawn by UPS battery
$Q_{UPS\_battery}$	Reactive power of UPS battery

2. Experimental assessment of UPS battery load model in the presence of harmonics

A detailed experimental work was performed during charging process on a 10 *kVA* single-phase (Nominal voltage: 230 *V*) UPS inverter battery (Make: Microtek; Model: Supermax Series-I) by using single-phase variac and an advanced Power and Harmonic Analyser (Model: PHA-5850; Make: Meco). Eight sets of readings were obtained by varying the voltage applied across UPS inverter battery (from 180 V to 260 V) and measuring various parameters using PHA-5850. Above experimental work was executed in two stages for developing a complete multi-frequency harmonic model of UPS battery. In the first stage, fundamental-frequency results of real, reactive and apparent powers were measured, while in the second stage, harmonic currents injected by the UPS inverter battery (magnitude as well as phase angles) were recorded for various voltage levels.

2.1. Fundamental-frequency results of power consumed by UPS battery during charging

Results of the experimental work are presented in per unit (*pu*) system for consistency in further analysis, by taking nominal rating of UPS battery as the base (10 *kVA*, 230 *V*). All experimental results have accordingly been indicated in per unit system; for instance, 6.6 *kW* real power drawn by UPS battery at 180 *V* in the first set of readings is represented as 0.660 *pu* real power at 0.783 *pu* voltage, as shown in Table 1 below:

Table 1. Experimental values of fundamental powers in UPS battery during charging

Voltage applied to UPS battery *(pu)*	Experimental values of powers at fundamental frequency during charging of *10 kVA* UPS battery		
	Real power *P(pu)*	Reactive power *Q(pu)*	Total power, *S (pu)*
0.783	0.660	0.578	0.877
0.826	0.660	0.593	0.887
0.870	0.656	0.604	0.892
0.913	0.656	0.615	0.899
0.957	0.656	0.653	0.925
1.000	0.656	0.668	0.936
1.087	0.656	0.675	0.941
1.130	0.656	0.683	0.947

From above experimental values, functional relation between voltage and power (real and reactive) has been obtained by using curve fitting tool in MATLAB, which is illustrated in Fig. 1. and 2:

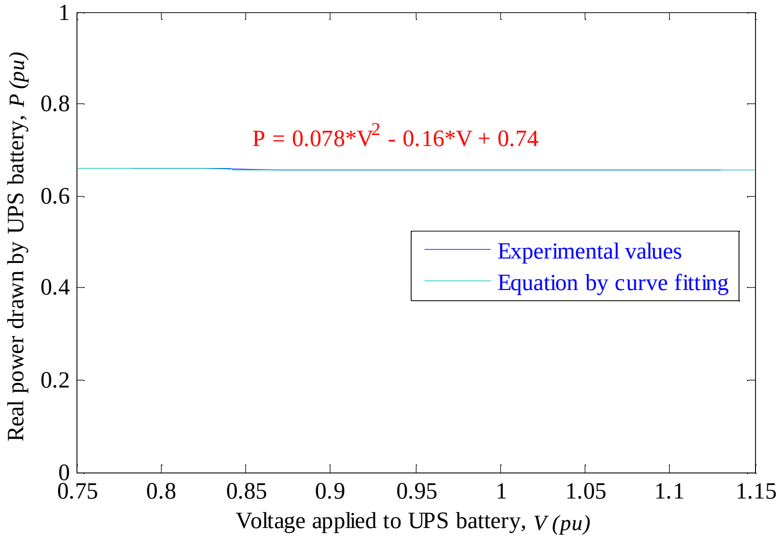

Fig. 1. Variation of fundamental real power (*P*) with voltage (*V*) in UPS battery

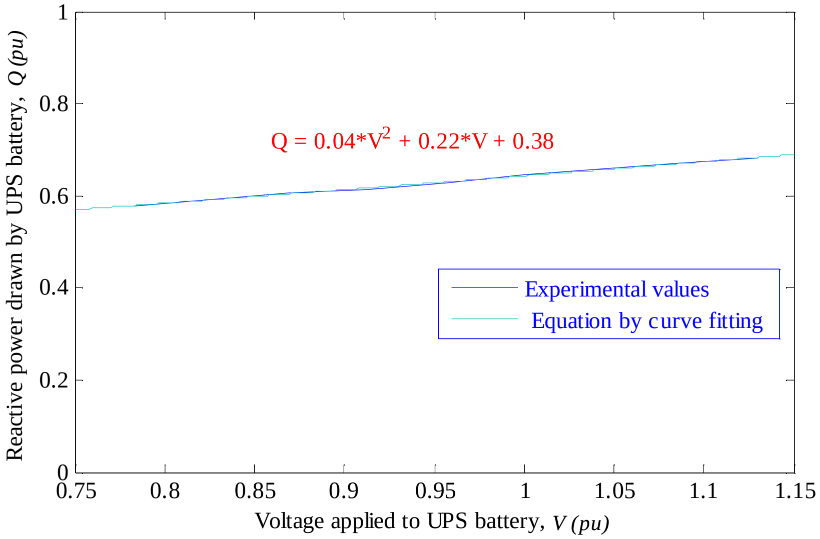

Fig. 2. Variation of fundamental reactive power (*Q*) with voltage (*V*) in UPS battery

2.2. *Results of harmonic currents injected by UPS battery during charging at various voltage levels*

Experimental results of second stage are shown in Table 2 by indicating harmonic currents in per unit and phase angles in degrees (°). As the values of harmonic current magnitudes beyond order 15 were measured to be negligibly small, hence the tabulated values have been limited only up to 15th harmonic order for simplicity in analysis.

Table 2. Experimental values of harmonic current magnitudes and phase angles in UPS battery during charging

Voltage applied to UPS battery *(pu)*	Experimental values of $\lvert I_h \rvert$ and $\angle\varphi_h$ for harmonic order *h* during charging of *10 kVA* UPS battery														THD_I value measured from the instrument (%)
	3		*5*		*7*		*9*		*11*		*13*		*15*		
	$\lvert I_3 \rvert$ *(pu)*	$\angle\varphi_3$ (°)	$\lvert I_5 \rvert$ *(pu)*	$\angle\varphi_5$ (°)	$\lvert I_7 \rvert$ *(pu)*	$\angle\varphi_7$ (°)	$\lvert I_9 \rvert$ *(pu)*	$\angle\varphi_9$ (°)	$\lvert I_{11} \rvert$ *(pu)*	$\angle\varphi_{11}$ (°)	$\lvert I_{13} \rvert$ *(pu)*	$\angle\varphi_{13}$ (°)	$\lvert I_{15} \rvert$ *(pu)*	$\angle\varphi_{15}$ (°)	
0.783	0.59	-138	0.38	-127	0.21	-131	0.03	142	0.12	171	0.11	-152	0.01	148	76.2
0.826	0.61	-146	0.39	-118	0.22	-133	0.03	127	0.13	159	0.12	-159	0.01	131	78.9
0.870	0.62	-148	0.39	-113	0.23	-137	0.03	119	0.13	143	0.12	-167	0.01	127	79.9
0.913	0.65	-153	0.41	-104	0.25	-139	0.04	108	0.15	134	0.14	-171	0.02	122	84.6
0.957	0.67	-159	0.42	-97	0.26	-142	0.04	93	0.17	124	0.15	-173	0.02	117	87.5
1.000	0.69	-164	0.44	-93	0.27	-147	0.04	89	0.18	116	0.16	-176	0.03	104	90.7
1.087	0.71	-168	0.45	-87	0.28	-152	0.04	78	0.19	107	0.18	-178	0.03	95	93.6
1.130	0.74	-176	0.46	-82	0.29	-156	0.05	71	0.21	98	0.19	-179	0.04	83	97.4

3. Mathematical framework for integrating experimental results to perform distribution load flow analysis with harmonics

3.1. *Fundamental and harmonic currents drawn by UPS battery during charging*

Total current drawn by UPS battery during charging process consists of the phasor sum of fundamental and harmonic currents, which can be mathematically expressed (in bold face) as:

$$\left[\boldsymbol{I}_{\boldsymbol{Total}}\right]_{UPS\_battery}=\left[\boldsymbol{I}_{\boldsymbol{1}}+\sum_{h=2}^{H}\boldsymbol{I}_{\boldsymbol{h}}\right]_{UPS\_battery} \tag{1}$$

In the proposed work, both current components on the right hand side if Eq. (1) are computed by using the experimental results as depicted in Section 2. The values of fundamental currents are obtained by using the functional relation between voltage and powers (real and reactive) as shown in Fig. 1 and 2, expressed by following mathematical Eqs.:

$$P_{UPS\_battery}=0.078*V_{UPS\_battery}{}^{2}-0.16*V_{UPS\_battery}+0.74 \tag{2}$$

$$Q_{UPS\_battery}=0.04*V_{UPS\_battery}{}^{2}+0.22*V_{UPS\_battery}+0.38 \tag{3}$$

By using well known relation between complex power, voltage and current [***S*=*V* *I****], the current phasor of UPS battery (***I₁***) at fundamental frequency can be represented by using conjugates of voltage and complex power, as:

$$\left[\boldsymbol{I}_{1}\right]_{UPS\_battery}=\left[\frac{\boldsymbol{S}}{\boldsymbol{V}}\right]^{*}_{UPS\_battery} \tag{4}$$

By substituting fundamental real and reactive powers as represented by Eqs. (2) and (3), Eq. (4) can be modified as:

$$\left[\boldsymbol{I}_{1}\right]_{UPS\_battery}=\left[\frac{P-jQ}{\boldsymbol{V}}\right]^{*}_{UPS\_battery} \tag{5}$$

As the values of real and reactive powers can be obtained in terms of voltage magnitude from the experimentally formulated Eqs. (2) and (3), a generalized expression of current $\boldsymbol{I_1}$ can be given as:

$$\left[\boldsymbol{I}_{1}\right]_{UPS\_battery}=\left[\frac{f_{1}(V)-j\,f_{2}(V)}{\boldsymbol{V}}\right]^{*}_{UPS\_battery} \tag{6}$$

Thus, complete phasor information of fundamental current flowing through UPS battery can be estimated for any voltage magnitude. It needs to be mentioned that Power and Harmonic Analyser used in above experimental work directly provides the spectral information (magnitude and phase) for harmonic currents injected by the UPS battery (Table 2). By adopting similar curve fitting approach, value of required harmonic current phasor for a particular harmonic order *h* (3 to 15) can be obtained for a given voltage level.

3.2. Total bus current in the presence of UPS inverter battery

Resultant current phasor of bus *i* consisting of its present load, along with the charging load of UPS inverter battery can be represented as:

$$\left[\boldsymbol{I}_{Resultant}\right]_{i}=\left[\boldsymbol{I}_{Bus\_Load}+\boldsymbol{I}_{UPS\_battery}\right]_{i} \tag{7}$$

By appropriate conversion of base values of the UPS battery current as per common base of the distribution system under investigation, resultant current of bus *i* can be computed in the presence of harmonics. Currents of all other buses can be calculated as per the given system data. Subsequently, a well-established backward/ sweep technique is applied to compute bus voltages and branch currents using suitable data structures [12].

4. Results and discussion

Experimental results as obtained in Section 2 are integrated with IEEE-18 bus RDS to study the impact of harmonic load model of UPS inverter battery. Load flow results are obtained for Total Harmonic Distortion (*THD*) of bus current and voltage of the RDS, along with real power consumption and losses at the substation [13, 14].

4.1. IEEE-18 bus RDS

Load and bus data of this RDS is taken from reference [15] and the system operates at the base power of 10 *MVA*. In this system, a UPS inverter battery of 1000 *kVA* (about 10 % of total load of given RDS) is assumed at bus no. *50*, having charging characteristics same as those obtained through above experimentation. Results of THD_V and THD_I are depicted in Table 3, while real power profile at the substation bus is shown in Table 4.

Table 3. *THD* of current and voltage for 18-bus RDS in the presence of UPS battery load

Bus No.	THD_I (%)	THD_V (%)
51	2.7	0.1
50	68.9	4.8
1	5.7	3.6
2	4.2	2.9
9	3.7	2.6
3	3.1	2.2
4	2.7	2.1
5	2.3	1.9
6	1.9	1.6
7	1.4	1.2
8	0.8	0.6
20	6.3	3.8
21	5.6	3.2
22	4.3	2.8
23	3.1	2.3
24	2.9	2.0
25	1.7	1.9
26	1.2	1.8

Table 4. Comparison of real power and loss profile at the substation bus

Parameter	Value without UPS battery	Value with UPS battery
Total real power at the substation (*kW*)	11881.2	12874.7
Total real power loss P_{Loss} (*kW*)	487.7	661.4
Loss (%)	4.03	5.14

4.2. Discussion on experimental and load flow results with UPS inverter battery

Experimental results of Section 2 indicate that UPS inverter battery during charging is a highly non-linear load, exhibiting large THD_I values (varying between 76.2 % to 97.4 %), with large values observed for higher voltage levels. Another significant feature during battery charging is noted in the variation of real and reactive powers with change in voltage. Real power drawn by UPS battery remains almost constant during variation of voltage from 180

V to 260 V, whereas reactive power is observed as increasing function of voltage. Also, all harmonic currents monitored by PHA are seen to increase with increase in voltage level.

From the load flow results obtained by applying experimentally determined harmonic model of UPS battery, considerably large THD_I value (68.9 %) is seen at the bus where inverter battery is installed (bus no. 50), causing voltage and current distortion in the downstream buses of distribution system under investigation. Furthermore, the buses nearer to bus no. *50* reveal more harmonic distortion as compared to farther buses. Results of real power consumption at the substation bus also indicate considerable increase in real power loss in the presence of UPS battery charging as compared to the loss without it (661.4 kW during UPS battery charging, and 487.7 kW in its absence), leading to increase in real power loss by 1.13 % of the entire distribution network.

5. Conclusion

In this paper, harmonic load modeling of a single-phase UPS inverter battery during charging has been demonstrated through a detailed experimentation by using an advanced Power and Harmonic Analyser. The experimental values are further integrated with a radial distribution system to investigate the effect of non-linear model of UPS battery on the distribution system. Experimental results have revealed that UPS battery is a constant real power load, exhibiting considerably large THD_I values during charging. On integrating battery charging load with the existing system, significant bus voltage and current distortions have been observed, consequently leading to increase in real power losses in the entire distribution network.

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