Electric Power Systems Research xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Economic assessment of phase reconfiguration to mitigate the unbalance due to plug-in electric vehicles charging

Matthew K. Gray, Walid G. Morsi*

Faculty of Engineering and Applied Sciences, UOIT Oshawa, ON, Canada

ARTICLE INFO

Article history:
Received 29 February 2016
Received in revised form 2 June 2016
Accepted 6 June 2016
Available online xxx

Keywords:
Distribution system
Power quality
Unbalance

ABSTRACT

This paper investigates the economic feasibility of a phase reconfiguration approach to mitigate the unbalance impact of plug-in electric vehicles using split-phase Level 1 charging on the secondary distribution system. The impact resulting from plug-in battery electric vehicles charging as single-phase loads in terms of reliability and power quality are quantified using a Monte Carlo Simulation. The cost-effectiveness of introducing phase reconfiguration in the secondary system is evaluated after mathematically formulating the phase reconfiguration as an optimization problem. The results have shown that the application of phase reconfiguration may result in a significant reduction in unbalance experienced by the system due to high penetration of plug-in battery electric vehicles taking into consideration the time of use pricing.

1. Introduction

In North America, the secondary distribution system typically starts at the distribution transformer and ends at the consumer's meter. The secondary system feeds power to residential consumers through two separate 120 V split-phase connections and a single 240 V full phase connection provided by a center-tapped distribution transformer as depicted in Fig. 1. While the split-phase configuration offers consumers both 120 V and 240 V connections, the resulting system may experience unbalance from uneven 120 V loading on the two split phases [1], in particular, when considering a cluster of Plug-in Battery Electric Vehicles (PBEVs) charging as single phase loads using Level 1 (120 V) charging.

While low penetration of PBEVs does not pose significant impact on the distribution system, continual increase of fuel costs paired with Government rebates such as those in Ontario, Canada [2] have begun to initiate large market penetration growth [3]. Considering the vast majority of PBEV are expected to charge at residential homes [4], the secondary distribution system, which connects these vehicles, may be susceptible to several power quality issues [5]. Furthermore, as electric vehicle chargers are able to provide power through a Level 1 120 V connection [6]; the secondary distribution system has the potential to experience unbalance, which has been found to cause undervoltage violations [7] and a maximum neutral voltage rise up to 4 V [5].

The assessment of distribution system unbalance due to PBEV charging has been studied in [8,9]. However, the unbalance investigation was limited to three-phase primary distribution systems, and did not consider the secondary system which feeds power to residential consumers and allows PBEV charging directly at homes. Studies [5,7,10] have assessed PBEV impact on secondary distribution systems and have reported up to 8% load unbalance [7] and 16% power unbalance [10] for 50% vehicle penetration. In response to the unbalance issues seen, studies [11–20] propose solutions to mitigate unbalance using methods such as: manual phase reconfiguration, transformer modification, and automated phase switching.

Voltage unbalance solutions on the distribution system were first used in reducing primary system unbalance through manual reconfiguration of the phase connections of primary laterals [12], resulting in a primary system zero sequence unbalance reduction of 1.108% to 0.070% and negative sequence unbalance from 0.880% to 0.072% respectively. Manual phase reconfiguration was further investigated in [13] to reduce the primary transformer unbalance from 11.7% to 0.3%. The work of [12,13] was extended to include rephasing of distribution transformer connections in [14], which reports the reduction of primary neutral current from 149A to 55A in the worst case considered. Given manual phase reconfiguration incurs significant costs due to manual labour required in performing phase reconfiguration as well as incurring customer interruption costs are large, primary phase reconfiguration was investigated for an economic assessment in [15], which was found to reduce feeder neutral current from 327A to 97A when performing phase reconfiguration using economic optimization. While manual phase reconfiguration was found to be economical, the practical obstacles of manual labour costs and customer interruption during rephasing

---

* Corresponding author at: University of Ontario Institute of Technology, Oshawa, ON L1H 7K4, Canada. Tel.: +1 905 721 8668x5483; fax: +1 905 721 3370.
E-mail address: walidmorsi.ibrahim@uoit.ca (W.G. Morsi).

http://dx.doi.org/10.1016/j.epsr.2016.06.008
0378-7796/

Please cite this article in press as: M.K. Gray, W.G. Morsi, Economic assessment of phase reconfiguration to mitigate the unbalance due to plug-in electric vehicles charging, Electr. Power Syst. Res. (2016), http://dx.doi.org/10.1016/j.epsr.2016.06.008

Nomenclature

Power flow variables

$[A]$	voltage phasing transfer matrix
$[B]$	voltage drop transfer matrix
$[C]$	current drop transfer matrix
$[D]$	current phasing transfer matrix
$[I_{ab}]_m$	split phase currents into downstream node m
$[I_{ab}]_n$	split phase currents into downstream node n
$[V_{ab}]_m$	split phase voltages at downstream node m
$[V_{ab}]_n$	split phase voltages at upstream node n

Phase reconfiguration variables

N	total number of phase reconfiguration devices in system
R	phase reconfiguration device index
x_R	line phasing state of phase reconfiguration device R

Optimization objective function variables

b_g	global best solution seen
b_j	best solution seen by solution particle j
j	solution particle index
p_j	position of solution particle j
v_j	velocity of solution particle j
φ	random number between 0 and 1

Optimization constraint variables

I^{ij}	branch current of line connecting nodes ij
$I^{ij}_{\max}$	branch current limit
I^{n}_{txf}	transformer neutral current
i	upstream node index
j	downstream node index
V^i	node i voltage
$V^i_{\max}$	node i voltage upper limit
$V^i_{\min}$	node i voltage lower limit

Economics variables

$C_{Customer}$	cost of customer reliability
$C^0_{Customer}$	cost of undervoltage violations without rephasing devices in system
$C^{N_{Device}}_{Customer}$	cost of undervoltage violations given N_{Device} rephasing devices in system
C_{Device}	cost of installing phase reconfiguration device
$C_{Energy}(h)$	cost of energy at time period h
C_{Labour}	cost of labour for fuse replacement
$C_{\text{Reliability}}$	cost of system reliability
$C^0_{\text{Reliability}}$	cost of reliability without rephasing devices in system
$C^{N_{Device}}_{\text{Reliability}}$	cost of reliability given N_{Device} rephasing devices in system
$C_{Utility}$	cost of neutral overloading incurred by the utility
d_v	duration of undervoltage violation event v
$ENS(h)$	cost of energy not supplied to secondary consumers at hour h
h	hour index
H	set of all hours in time period considered
i	interruption event index
I	total number of interruption events
N^i_{Cust}	number of customers affected for interruption event i
N^v_{Cust}	number of customers experiencing voltage violation in undervoltage event v
N_{Device}	number of phase reconfiguration devices in system
R_{PQ}	revenue earned from power quality improvement
$R^{N_{Device}}_{PQ}$	revenue saved from power quality improvement due to inclusion of N_{Device} rephasing devices
$R_{\text{Reliability}}$	revenue earned from system reliability improvement
$R^{N_{Device}}_{\text{Reliability}}$	revenue saved from reliability improvement due to inclusion of N_{Device} rephasing devices
v	undervoltage violation event index
V	total number of undervoltage violation events
WTP	customers' willingness to pay to avoid an outage in terms of dollars
$WTP_{UV}(d_v)$	customers' willingness to pay to avoid undervoltage event of duration d_v

Monte Carlo variables

d	daily distance driven by a PBEV
e	specific energy of the PBEV
E_b	battery capacity of the PBEV
i	Monte Carlo trial index
N_{trials}	total number of Monte Carlo trials
$SOC_{\min}$	minimum allowable state of charge of the PBEV
η	charger efficiency
$\overline{\Psi}$	expected profit of Monte Carlo simulation
$\Psi(i)$	profit determined from Monte Carlo trial i

typically results in limiting utilities to two reconfiguration events per year, with no further unbalance mitigation between rephasing events. The work of [16] proposes the usage of sectionalizing switches and unbalance distributed generator injections to minimize primary system unbalance at an hourly resolution from 3.47% to 3%. While sectionalizing switches and distributed generators offer real-time control and do not suffer from manual reconfiguration limitations, such components are typically limited to primary systems and cannot be adapted to the secondary system.

The idea in [17] proposes the usage of Scott transformers to passively reduce primary system unbalance. While this method eliminates the need of manual labour costs and continuously balances the system, the cost of additional transformers required in the proposed method is significant, and the resultant phase balancing benefits are seen only on the primary system and do not improve secondary unbalance.

In response to the lack of secondary unbalance solutions, a number of recent methodologies have been proposed to limit the distribution systems unbalance using active solution methods. The work of [18] proposes the usage of three-phase EV chargers, which may perform phase balancing through single phase power loading and injection, and was found to reduce expected voltage unbalance from 0.70% to 0.25% on system node 62. While the three-phase EV chargers in [18] provide significant unbalance reduction in the system, the burden of purchasing more expensive three-phase chargers is placed on the residential customer whom is not responsible for maintaining system operating conditions, and therefore is impractical. Similar solutions to mitigate unbalance have been

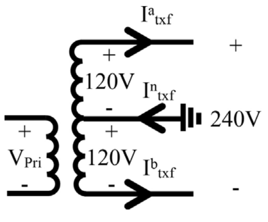

Fig. 1. Center-tapped transformer secondary winding.

Please cite this article in press as: M.K. Gray, W.G. Morsi, Economic assessment of phase reconfiguration to mitigate the unbalance due to plug-in electric vehicles charging, Electr. Power Syst. Res. (2016), http://dx.doi.org/10.1016/j.epsr.2016.06.008