Impact of DLC Programs Levels on Reliability Improvement of Smart Distribution Network considering Multi Carrier Energy Networks

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Abstract

In modern Smart Grid paradigm, through introducing demand-responsive proactive consumers, energy storage systems and renewable energy resources spread across the distribution network, the inherent of the service restoration problem changes from an all-or-none solution to selective restoration through smart meter and Distributed Energy Resources (DERs). Combined Heat and Power (CHP) is a great example of the technologies which allows coupling of multi carrier energy networks such as gas and electricity together in response to future energy infrastructures. In this paper, a practical and initiative method is presented to obtain the most optimal arrangement of supplying loads in each micro grid based on Energy Hub approach. In this paper, we examine the effect of various procedures of DLC programs (such as interrupt at the level of transformers or small groups of customers) of Demand Response (DR) on reliability indices in multi carrier energy networks. Simulation is applied on a 33 bus radial distribution network which supplies by two CHPs. MATLAB is employed to determine optimal combination of selected loads and transformers. Due to failure rate and repair time of each section, Outage cost, ASIDI and ENS indexes are calculated. Simulation results show that DLC at the level of small groups of customers reduces huge total costs 11-12% and 3-4% in comparison to DLC at the level transformers and without DLC program, respectively.

1. Introduction

Smart grid enables and empowers DERs in distribution network level through progressive advanced technologies. Combined Heat and Power (CHP) is a great example of the technologies with significant benefits of efficiency, reliability and economic improvement which allows integrating of multi carrier energy networks such as electricity, gas, district heat and etc. Integration of DERs; Wind, energy storage and Demand Response programs (DR) to the networks could be beneficial for electrical network companies in order to prevent investment costs of expansion transmission lines and conventional generation plant establishment and also to improve network loss, voltage and reliability. It could be also profitable for customers to reduce their operation cost.

Integrated energy systems have been considered recently as "Micro Grid" [1], "Hybrid Energy Hub" [2], the latest approach originates in VOFEN (Vision of Future Energy Network) project [3] which defines "Energy Hub" as a super node in electrical power system to receives varying energy carriers such as gas and electricity in its input, then strongly schedules when and how much of which carrier should be purchased and stored to provide hub required demands. EH simplifies multiple systems optimization both in operation and planning). (See Ref.[4],[5] for hub and interconnected hubs optimization. EH approach isn't restricted to predefined concept. The model could be flexibility expanded by DERs [6] in; big buildings, Industrial plants, bounded geographic areas and Island systems.

A hybrid energy system with wind and DR is economically scheduled in [7] which DR effect on reliability assessment isn't considered in the paper. Multi carrier energy networks are dependently operated in presence of DR and without reliability effect of the system in [8]. A commercial energy hub is scheduled based on operation cost and reliability impact of energy not supplied in the system in [9] which Demand response program with its effect isn't studied in the paper. Effect of DR and ES on residential EH which is supplied with Photo Voltaic is comprehensively examined in [10] which reliability effect of DR isn't considered in the paper. A financial analysis of EH which is equipped with Demand side management of het load without considering its reliability effect on the system is evaluated in [11-12]. DR is applied on a residential EH with Model Predictive Control in order to manage household micro CHP in [13] which reliability effect of DR isn't examined in the paper. Finally, reliability effect of EH in comparison with independent energy networks without DR and its reliability impact is evaluated in [14]. In addition, direct load control [15], [16], has been shown to be a viable way to control the power system toward desirable operating conditions. Concurrently, effective load management could also be employed when determining switching schemes.

This paper is organized to assess reliability effect of DR program implementation in multi carrier energy networks based on EH approach as follow: Problem is mathematically formulated in section 2. Methodology of problem is explained in section 3. Section 4 evaluates simulation results. Finally, conclusion is debated in section 5.

2. Problem Formulation

In this context, problem is mathematically formulated in objective function and its constraints as follow:

2.1 Objective Function

Multi carrier operation costs and Energy Not Supplied (ENS) costs due to DR implementation are formulated in objective function (1) [17].

$$of = Ct^{Op} + Ct^{ENS} \tag{1}$$

2.2 Operation Costs in Multi Carrier Energy Networks under EH approach

Hub decides that when and how much of which energy carrier should be purchased in required times in order to satisfy hub electricity and heat required demands in response to minimization of operation costs.

Electricity power P_e^{Net}, gas powers for CHP P_g^{NetCHP} and for boiler P_g^{NetB} are purchased according to electricity π_e^{Net} and π_g^{Net} gas prices. Additional produced electricity and heat $P_h^{Netsold}$ with electricity and π_h^{Net} heat prices are also sold to grid to achieve revenue in order to reduce operation costs (2). *h* shows hours indices for one year and *b* introduce bus numbers of electrical network in the function.

$$Of = \sum_{b=1}^{B}\sum_{h=1}^{8760}[\pi_e^{Net}(h)\, P_e^{Net}(h)] + \left[\pi_g^{Net}(P_g^{NetCHP}(h) + P_g^{NetB}(h))\right] - \left[\pi_h^{Net} P_h^{Netsold}(h)\right] \tag{2}$$

Hub required electricity demands P_e could be supplied by network electricity power in required times. CHP can also produce electricity power from converting imported gas power to electricity through its efficiency η_{ge}^{CHP}. Wind power P_e^{w} could be able to produce free and clean electricity power through its efficiency η_{ee}^{Con} in (3).

Hub required heat demands P_h could be supplied by produced heat by CHP through its gas to heat efficiency η_{gh}^{CHP} or boiler through its gas to heat efficiency η_{gh}^{B} in (4).
Sum of imported gas power for CHP and boiler should be restricted by gas network constraint P_g^{Net} in (5). Imported gas power for CHP and for boiler could be respectively limited by CHP P^{CHP} and boiler P^{B} capacities in (6) and (7).

$$P_e(h,b) = [P_e^{Net}(h,b)] + \left[\eta_{ge}^{CHP} P_g^{NetCHP}(h,b)\right] + [\eta_{ee}^{Con} P_e^{w}(h,b)] \tag{3}$$

$$P_h(h,b) = [\eta_{gh}^{CHP} P_g^{NetCHP}(h,b)] + \left[\eta_{gh}^{B} P_g^{NetB}(h,b)\right] \tag{4}$$

$$P_g^{Net}(h,b) = P_g^{NetCHP}(h,b) + P_g^{NetB}(h,b) \tag{5}$$

$$\eta_{ge}^{CHP} P_g^{NetCHP}(h,b) \le P^{CHP} \tag{6}$$

$$\eta_{ge}^{B} P_g^{NetB}(h,b) \le P^{B} \tag{7}$$

2.3. Reliability

When fault occurred in each section λ_{br} with its length L_{br} portion of the loads, which are not exposed in micro grid or have been interrupted due to Direct Load Controller (DLC) program will be interrupted until the damaged section is repaired in repair time tre $t_{re}$and rest of loads are retrieved with DER. t_{sw} shows switching time. Due to the condition of generation, loads and DLC infrastructures in forming micro grids per fault, each load will be placed in one of these two situations. Consequently, total

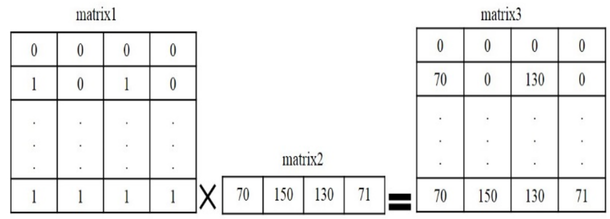

Fig. 1. All status of Transformers combination in each micro grid

outage time for each line is calculated and through this reliability indexes and outage cost is obtained. Energy Not-Supplied index (ENS) and Average Sustained Interruption Duration Index (ASIDI) which are considered as reliability indices for this paper. Hence, system disruption cost Ct^{ENS} according its Cost Damage Function [18] can be evaluated as represented in following equation [19]:

$$Ct^{ENS} = \sum_{br=1}^{Br} \lambda(br).L(br)\Big(\sum_{b=1\ E\ Isl}^{B} CDF(b)LP(b).t_{sw} + \sum_{b=1\ Isl}^{B} CDF(b)LP(b).t_{re}\Big) \tag{8}$$

$$ASIDI = \frac{\sum_{b=1}^{B} LP(b).t_{re}}{\sum_{b=1}^{B} LP(b)} \tag{9}$$

2.4. Network Constraints

Electrical grid P_e^{Netmax}, gas network P_g^{Netmax}, thermal limits of each branch S_{br}^{max} and voltage of each bus V_b^{min}, V_b^{max} constraints should be applied in the problem in equations (10), (11), (12) and (13) in sequence.

$$\sum_{h=1}^{8760} P_e^{Net}(h,b) \le P_e^{Netmax} \tag{10}$$

$$\sum_{h=1}^{8760} P_g^{Net}(h,b) \le P_g^{Netmax} \tag{11}$$

$$S_{br} \le S_{br}^{max} \tag{12}$$

$$V_b^{min} \le V(h,b) \le V_b^{max} \tag{13}$$

3. Methodology of Problem

One of the main constraints to supply the loads in each micro grid is keeping frequency stability through maintaining a balance between production and consumption. In some conditions, sum of DERs generation in micro grid is less than total loads. Thus, operator curtails all loads until the affected section is repaired and micro grid connected to the main grid. As a result, some micro grids in each fault would be dysfunctional.
There are two basic solutions to decrease interrupted loads in micro grids, 1) increase generation level of each micro grid by installing new DERs and 2) decrease the loads in each micro grid until production and consumption are balanced. In this paper the second solution is discussed. Two level of direct load

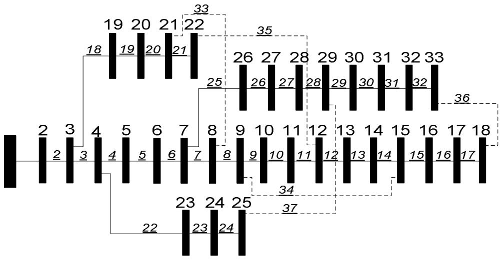

Fig. 2. Radial distribution network under study

Table 1. Information of radial distribution network under study

Bus No.	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Load(kW)	36	185.3	42.8	21.4	21.4	7.1	72	21.4
Bus No.	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Load(kW)	21.4	16	354	21	42.8	21.4	21.4	21.4
Bus No.	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Load(kW)	32.1	32.1	32.1	32.1	253	32.1	151.2	593.2
Bus No.	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**
Load(kW)	21.4	21.4	21.4	43.1	72	55.9	605	21.4

Table 2. Parameters values

Gas price	5	Heat price	10
Boiler capacity	1500	Boiler efficiency	0.9
Electricity grid capacity	6MW	Gas network capacity	5.5MW
Network availability	0.99	*CHP availability*	0.96
Domestic CosΦ	0.95	Domestic CDF	10$/kWh
Commercial CosΦ	0.9	Commercial CDF	20$/kWh
Industrial CosΦ	0.85	Industrial CDF	30$/kWh
V_r,C	220,3	V_m	210-250

Table 3. Reliability indices in three level of DLC program with considering two CHP

	Outage Cost($)	ASIDI (hrs.)	ENS(kWh)
Without DLC	255620	1.046	10632
Transformer Level DLC	241842	0.9867	10001
Customer Level DLC	232314	0.9453	9721

control programs are proposed to determine the impact of each program on reliability indices.

In some situations, control Infrastructures are installed at the level of direct control of power distribution transformers. Consequently, if generation and consumption level in each micro grid is not balanced the operators instead of curtailing all loads, curtail transformers one by one from the least important to the most important until the consumption equal to generation. Compared to traditional state more loads are restored. Therefore, the reliability indices are improved. If more advanced level of communication and controls infrastructure are installed, the operators can control small groups of customers or various levels of large loads. Thus, the largest portion of loads in each micro grid is restored in comparison with two previous conditions.

In this paper, two level of DLC program is proposed to implement selective restoration with considering CDF and load importance.

To operate DLC program at the level of transformer, select the transformers with higher outage cost for restoring is a priority. First the capacity of transformers in each micro grid is added together, if sum of them less than total generation in micro grid, all of them are selected to restore. Otherwise, the operator should select optimal combination of transformers to restore. In this paper, a practical and initiative method is presented to obtain the most optimal arrangement of supplying loads in each micro grid. Permutations theorem is used for solving this problem. For example, if four transformers are located in a micro grid, there are 16 states of transformers restoration combination, from curtailed all of them to restored all of transformers. All status of transformers arrangement in each micro grid is shown in Fig.1. A matrix which contain all states of on/off transformers (matrix1) and matrix of transformers capacities (matrix2) is generated. The second state of matrix (1) for instance, means transformers 1&3 are restored and transformers 2&4 are curtailed. Each row of first matrix dot to second matrix determines total capacity of transformers in each proposed state (matrix3).

Some states of matrix (3) are eliminated because total capacity of loads is greater than total generation of that micro grid. To select optimal combination of transformers among allowable states, power of each curtailed transformer is multiplied in the outage cost of loads which connected to this transformer. After calculation of the outage cost of each state, a state that the sum of outage cost is minimum will be selected. Operator should curtail the transformers which are zero in selected combination to maintain frequency stability and minimize penalty for interrupting.

To implement DLC program at the level of small groups, after determine the optimal combination of transformers, the curtailed transformers with higher outage cost are selected. Due to load resolution and accessible level of load control, small groups of loads are added to restoration list until difference between consumption and generation is minimized. In this paper, the resolution of loads that operators able to control them directly in residential, commercial and industrial sectors assume 5, 10 and 20 kW respectively. To calculate repair time for these transformers, due to the ratio of total load that were restored in curtailed transformer to the capacity of that transformer, this healthy percentage of transformer is determined as loads which restore by DERs in reliability calculation. In this situation, the maximum generation capacity of a micro grid will be used. As a result, the efficiency of micro grid is improved.

4. Simulation result

Simulation is applied on a radial distribution network with 33 buses in Fig. 2 according to its loads powers in Table 1. This network includes 32 load points and a subsystem with 37 branches [20]. CHPs characteristics with other parameters are shown in Table 2.

To determine the performance of each condition, two CHP with the capacity of 800 and 600 kW were installed in buses 12 and 25, respectively. ASIDI, AENS and Outage cost of each DLC program is illustrated in Table 3.

Outage cost, ASIDI and ENS of distribution network after implement DLC in transformer level Improved approximately 8% as compared to without DLC program state. . Numerical results demonstrate the accuracy of proposed method. Also, when operators able to control small groups of customers (third state), the reliability indices are improved approximately 3-4%

Table 4. Reliability indices in three level of DLC program without CHP

	Outage Cost($)	ASIDI (hrs.)	ENS(kWh)
Without DLC	292600	1.1886	12264
Transformer Level DLC	292600	1.1886	12264
Customer Level DLC	292600	1.1886	12264

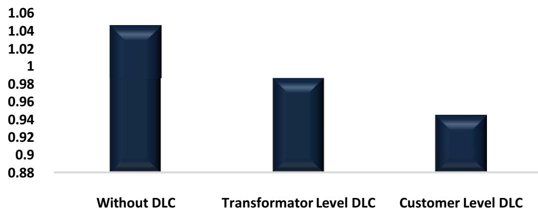

Fig. 3. ASIDI index in 3 level of DLC program

as compared to transformer level DLC program state. For better displaying the differences between these three scenarios of DLC program, ASIDI and outage cost are shown in Fig. 3 and Fig.4, respectively.

This difference between reliability indices with considering DLC programs and a without this ability is occurred when at least one DER is installed and operated in distribution network. Otherwise, only two types of micro grids are formed after a fault. Some of them connected to man grid and others are created in downstream without alternative resources. In first state, all loads can restore without need to load curtailment. In second state all loads are disconnected to any supplier. Therefore all loads are de-energize until the fault section is repaired. Table 4 demonstrates the reliability indices of a distribution network without any CHP.

The result shows direct load control ability without presence of DERs cannot increase distribution network efficiency.

5. Conclusions

Over the past two decades, utilization of multi carrier energy networks has been originated as sufficient solution to cope with huge investment costs of transmission lines expansion and power plants establishment in response to growing energy needs and greenhouse gases emissions. With Considering key position and shape of micro grids, number of DERs and loads with different importance will be placed in micro grids. A portion of loads which are not exposed in micro grid or have been interrupted due to DLC program will be off until the damaged section is repaired. Due to various CDF of each load how to select the candidate loads for restoring has a major impact on final outage cost. In this paper, three types of load shedding were examined on multicarrier energy networks and then impact of the DR programs on reliability of the systems is assessed. In first step, the network is unable to implement selective load curtailment. In second step, control infrastructures at the level of power distribution transformers are installed. With considering generation level in each micro grid, capacity of transformers and importance of loads which connected to

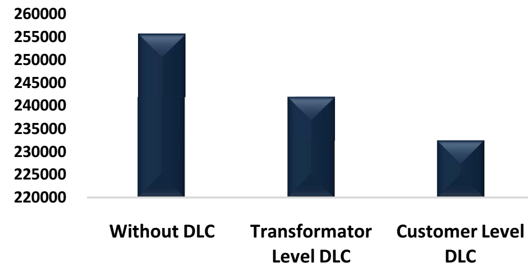

Fig. 4. Outage cost in 3 level of DLC program

transformers, some transformers are restored and reliability indices are improved. Results was illustrated that ASIDI and ENS are improved 8-10% in comparison with traditional outage management. In third step, operators can control smaller resolution of loads by smart meter and other control equipments. Simulation result was demonstrated DLC at the level of small groups can improve ASIDI and ENS approximately 3-4% in comparison with previous step. Also, to improve the efficiency of DLC program in distribution network, the penetration of DERs should be increased.

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