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Reliability/Cost-based Power Routing in Power Electronic-based Power Systems

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Abstract—**This paper proposes a unified power routing strategy for optimal and reliable operation of power electronic-based power systems. The overall reliability of the system will be enhanced by devolving the load of highly damaged power converters to lowly damaged ones. However, it may introduce higher operational costs for lowly damaged converters. Therefore, the reliability support from these converters will be performed with respect to their operational costs. This will guarantee lower operational costs and higher reliability of the system in addition to preventing over-stressing of converters. The simulations and numerical analysis illustrate that the proposed approach has higher reliability compared to the conventional approach and lower operational costs compared to the pure reliability-oriented methods.**

Keywords— reliability, power converter, power routing, operational cost, reliability cost-worth.

I. Introduction

Power electronics have become a backbone of modern interconnected power and energy systems. They can affect power systems performance in short- and long-term by posing stability [1] and reliability challenges [2]. From a reliability stand-point, power converters can be the source of failure, downtime and its costs in power systems [3]–[6] in the case they are not appropriately designed or operated. Thus, safe and secure operation of modern power systems require advanced solutions which guarantee overall reliability and resilience of power systems.

There are various system-, and converter-level techniques to enhance and strengthen the reliability as well as resilience of power electronic-based power systems. The main system-level solution for enhancing the reliability of future power systems is to develop distributed systems both in structure and control. Thus, microgrids have become a promising technology providing infrastructure for distributed resources and power/energy management. Furthermore, microgrids aid islanded operation of power grids to support critical loads in the case of grid outage, and hence, reducing the risk of customer interruption. Moreover, power electronics are the essential part of microgrids, and the performance of microgrids are affected by the converters. Since in the islanded mode, a microgrid is more sensitive to any disturbances, the outage/failure of converters can deteriorate its functionality.

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The converter reliability depends on various failure causes including catastrophic and wear-out failures [7]–[9]. The catastrophic failures are usually triggered by an extrinsic cause; thus, it is very difficult to model and mitigate them. Meanwhile, the wear-out failure mechanisms are intrinsic, and controllable. The wear-out failure in power converters are usually occur in power devices and electrolytic capacitors. Various failure mechanism in power devices and capacitors are summarized in [10]. According to filed experience, these components are the most fragile components in various application. Therefore, the converter reliability can be improved by preventing the aging of converter components.

There are several methods to enhance the reliability of converters which are essentially divided into two main categories of design and control domains. Design of converters is associated with the planning of microgrids, and the control of converters is attributed to the operation of microgrids. Therefore, their mechanisms on the reliability improvement will cover both short- and long-term effects. During design and manufacturing the converters, their components are selected according to a desired reliability performance, usually a life cycle with a specific probability of survival. Moreover, recently, system level design for reliability is presented to design a converter with respect to the power system performance, which takes into account the converter application and its function in power system [11]–[13]. In addition to design for reliability, preventive maintenance approaches [14] can be employed during the planning of a microgrid in order to do cost-effective design of a converter for a specific period of mission.

Moreover, the converter reliability can be improved within operation using appropriate techniques such as adaptive switching frequency [8], advanced switching techniques [15], reactive power routing [16], [17] and preventive maintenance and active power sharing [18].

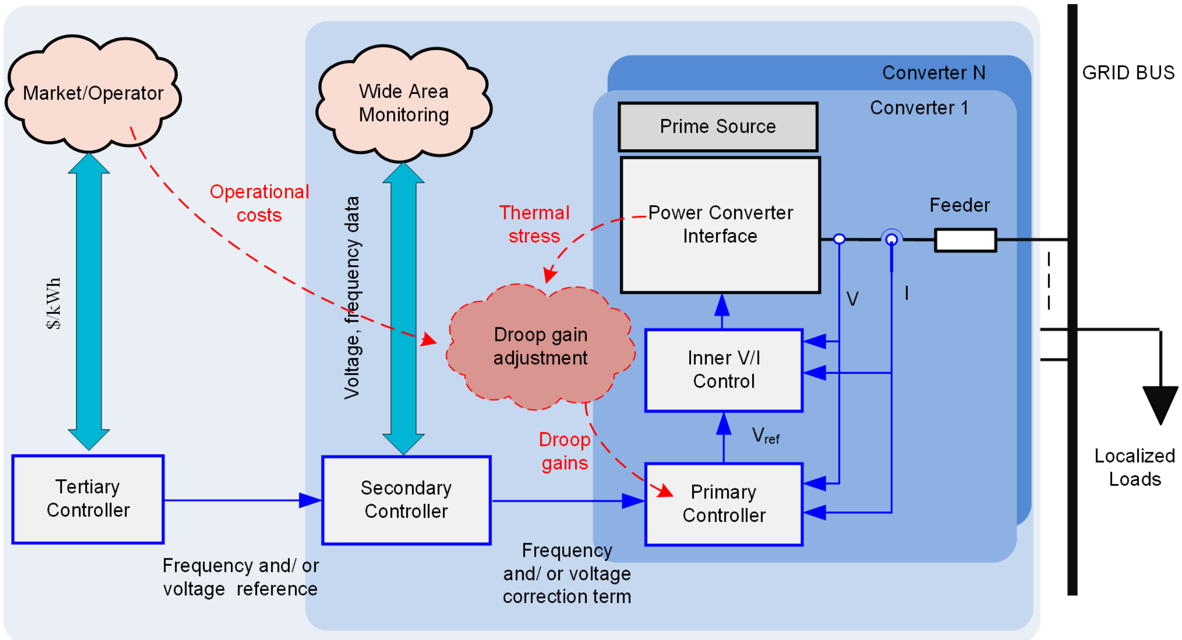

Fig. 1. Control structure of power electronic converters in modern power systems.

Furthermore, condition monitoring and fault diagnostics during operation can help enhancing the reliability of converters [19]–[21]. Moreover, power routing among converters based on their thermal stresses or loading conditions can have remarkable impact on the system reliability as it can dynamically distribute the thermal damages of the converters among them [17], [18], [22]. This concept indeed act as an online and active maintenance where the loading of highly damaged units can be moved to the converters with low thermal damage.

The power routing among DC-DC converters based on reliability considerations is addressed in [18], [22]. Furthermore, reactive power sharing based on the thermal damage of the converters in AC microgrid is presented in [17]. In practice, shifting the load of highly damaged converter to a lowly damaged one may introduce extra operation costs. Notably, operational cost based power routing in microgrids has already addressed in [23]. However, the thermal stress of units is not considered in this study, thus the reliability of the system may not be guaranteed.

In order to address this issue, this paper proposes a unified reliability/cost-based power routing approach in power electronic-based power systems. The proposed approach aims to enhance the overall system reliability with respect to the operational costs of the power units. As a result, besides the conventional power sharing approaches merits like preventing overstressing of converters, the cost-effective and reliable operation of them will also be obtained.

The details of the proposed power sharing method and its basics are presented in Section II. The effectiveness of the proposed power routing approach is illustrated on a DC power electronic-based power system in Section III. Finally, the outcomes are summarized in Section IV.

II. Proposed Power Routing Approach

Typical control structure of a power electronic converter in a power system is shown in Fig. 1. The control system is hierarchically performed in three levels; tertiary level for economical operation, secondary level for voltage frequency regulations and primary level for power balance/sharing control. Conventionally, power sharing among sources has been performed using droop scheme. In this approach, the loading of each unit is proportional to its rated power. Thus, it prevents overloading of converters under various operating conditions [24]. This paper, introduces advanced droop technique to prevent overloading of converters, overstressing of converters and at the same time minimizing the operational costs of the units. The proposed approaches are explained in the following.

A. Proposed advanced droop scheme

According to the droop approach, the frequency can be proportionally controlled by output power in AC grids following (1), where ω, ω_0 are the actual and reference angular frequency, k_p is the droop gain and P is the output power. Similarly, in DC grids, the voltage is controlled proportional to the output power following (2), where V, V_0 are the actual and rated DC voltages.

$$\omega = \omega_0 - k_p P \quad (1)$$

$$V = V_0 - k_p P \quad (2)$$

This technique takes into account the rated power (current) of the units to prevent overloading. However, according to the lifetime of power devices, not only does the load level affect its reliability, but also the loading fluctuations may limit the life expectancy of power converters [5]. Thus, even the conventional approach prevents the overloading of converters, it may not avoid overstressing and aging of units [17]. Therefore, the reliability-oriented methods have been presented to address this issue, where the loading of converters are controlled using (3) and (4) for AC and DC grids [17], [18].

$$\omega = \omega_0 - \frac{D}{D_{\max}} P \tag{3}$$

$$V = V_0 - \frac{D}{D_{\max}} P \tag{4}$$

where D is the thermal damage of corresponding unit and D_{max} is the maximum damage of the units. According to this method, the loading of highly damaged unit is shifted to the lowly damaged one. This can improve the system reliability while it may cause higher operational costs. In fact, there is a compromise between reliability and operational costs in microgrids. To address this issue, the reliability/cost-based control approach is proposed in this paper.

$$\omega = \omega_0 - \frac{D}{D_{\max}} \frac{C}{C_m} P \tag{5}$$

$$V = V_0 - \frac{D}{D_{\max}} \frac{C}{C_m} P \tag{6}$$

where C is the operational cost of corresponding unit and C_{max} is the maximum operational cost of the units in the grid. In the following, the converter damage analysis and operational costs model are presented.

B. Converter damage modeling

The reliability and damage of a converter depends on its loading and climate conditions [25], [26]. These conditions cause wearing out of converter components, thus limiting its useful lifetime. According to the field returned data, capacitors and semiconductor devices are the two most fragile components in power converters [25]–[29]. The semiconductors lifetime can be modeled as the number of cycles to failure, N that the device withstands without according a failure. According to (7), this depends on the junction temperature variations ΔT_j, its minimum value T_{jm}, and its heating time t_{on} [30], [31].

$$N = A \cdot \Delta T_j^{\alpha} \cdot \mathbf{exp}\left(\frac{\beta}{T_{jm} + 273.15} \right) t_{on}{}^{\gamma} \tag{7}$$

where A, α, β, and γ are obtained based on field experience or from lifetime tests [30]. Thereby, the thermal damage of a semiconductor device is obtained using minor rules as:

$$D^{(sem)} = \sum_t \frac{n_t}{N_t} \tag{8}$$

where $D^{(sem)}$ denotes the thermal damage on the semiconductor devices experiencing n_t power cycles within the period of t. Moreover, N_t is the number of cycles to failure in the applied loading profile which is associated with T_{jm}, ΔT_j, and t_{on} obtained from (7). The wear out of power devices such as Insulated-Gate Bipolar Transistor (IGBT) and diodes can be obtained suing (8).

Moreover, the wear out of the capacitors can be estimated employing its lifetime model, e.g., using lifetime model represented in (9) [32].

$$L_w = L_r \cdot 2^{\frac{T_r - T_w}{n_l}} \left(\frac{V_w}{V_r} \right)^{-n_2} \tag{9}$$

Where, L_r, V_r, and T_r, denote the nominal lifetime, voltage and temperature of capacitor. Moreover, L_w, T_w, and V_w are the lifetime consumption, temperature and voltage due to applied mission profile. As a result, the capacitor damage, $D^{(cap)}$ under given operational conditions can be obtained as:

$$D^{(cap)} = \sum_t \frac{\Delta T_w}{L_{w,t}} \tag{10}$$

where, ΔT_w is the time interval w that the capacitor experiences T_w, and V_w and the corresponding lifetime consumption will be L_w based on (9).

Finally, the average thermal damage per converter's component, D, is obtained as:

$$D = \frac{1}{M^{(sem)} + M^{(cap)}} \left(\sum_j^{M^{(sw)}} D_j^{(sem)} + \sum_j^{M^{(cap)}} D_j^{(Cap)} \right) \tag{11}$$

where, M denotes the number of each component in the convert.

C. Operational costs modeling

The operational costs of energy units depend on different factors based on the initial energy source, environmental pollutions, maintenance costs, etc. Operational costs, C are usually modeled by a second-order quadratic expression such as[23]:

$$C(P_x) = a + b \cdot P_x + c \cdot P_x^2 \tag{12}$$

where, the term a is in charge of no-load costs, b is associated with the maintenance costs, c is attributed with the fuel and emission costs. This curve is shown in Fig. 2 indicating the incremental operational costs by increasing the load of units. During shifting the load of one unit to the other unit the decremental cost of first unit will be smaller than the incremental costs of the second one. Therefore, load adjustment may improve the reliability of the system, while it can introduce higher operational costs.

The proposed approach relies on optimizing the reliability per costs of operation in the system. According to this approach, the unit with higher thermal damage should support lower power to enhance the system reliability. On the other hand, the unit with higher operational costs will support low power to decrease the overall operational costs. As a result, there is a compromise between operational costs and the reliability of the system, and the system can be operated in an optimal point maximizing the reliability while minimizing the operational costs. This can be implemented by an advanced droop control given in (5) and (6) for AC and DC grids. In the following a case study is provided in DC grid to show the performance of the proposed control scheme to enhance the reliability and cots of operation.

III. Numerical Analysis

In this section, a simulation on a DC power electronic-based power system is presented. The DC grid includes a solar photovoltaic (PV) unit, fuel cell (FC) stack, microturbine (MT) and battery storage as shown in Fig. 3. The PV system specifications are given in TABLE I. The solar irradiance and ambient temperature are shown in Fig. 4(a, b) respectively. Furthermore, the annul load profile is shown in Fig. 4 (c). The operational cot of energy units is given in Fig. 5. Moreover, the converter specifications are summarized in TABLE II. Notably, the proposed approach is applicable for AC power systems as well without losing generality.

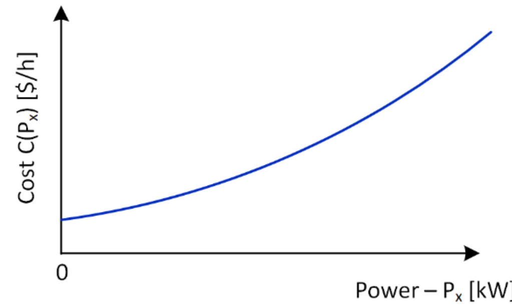

Fig. 2 Operational cost of an energy unit.

TABLE I PV SYSTEM SPECIFICATIONS.

Parameter	Value
Panel Rated Power	345 *W*
Number of Series panels in string	5
Number of Parallel strings	3
Open Circuit Voltage	64.8 *V*
Short Circuit Current	7.04 *A*
MPPT Voltage	54.7 *V*
MPPT Current	6.26 *A*
Voltage temperature Coefficient	-0.27 *%/K*
Current temperature Coefficient	0.05 *%/K*

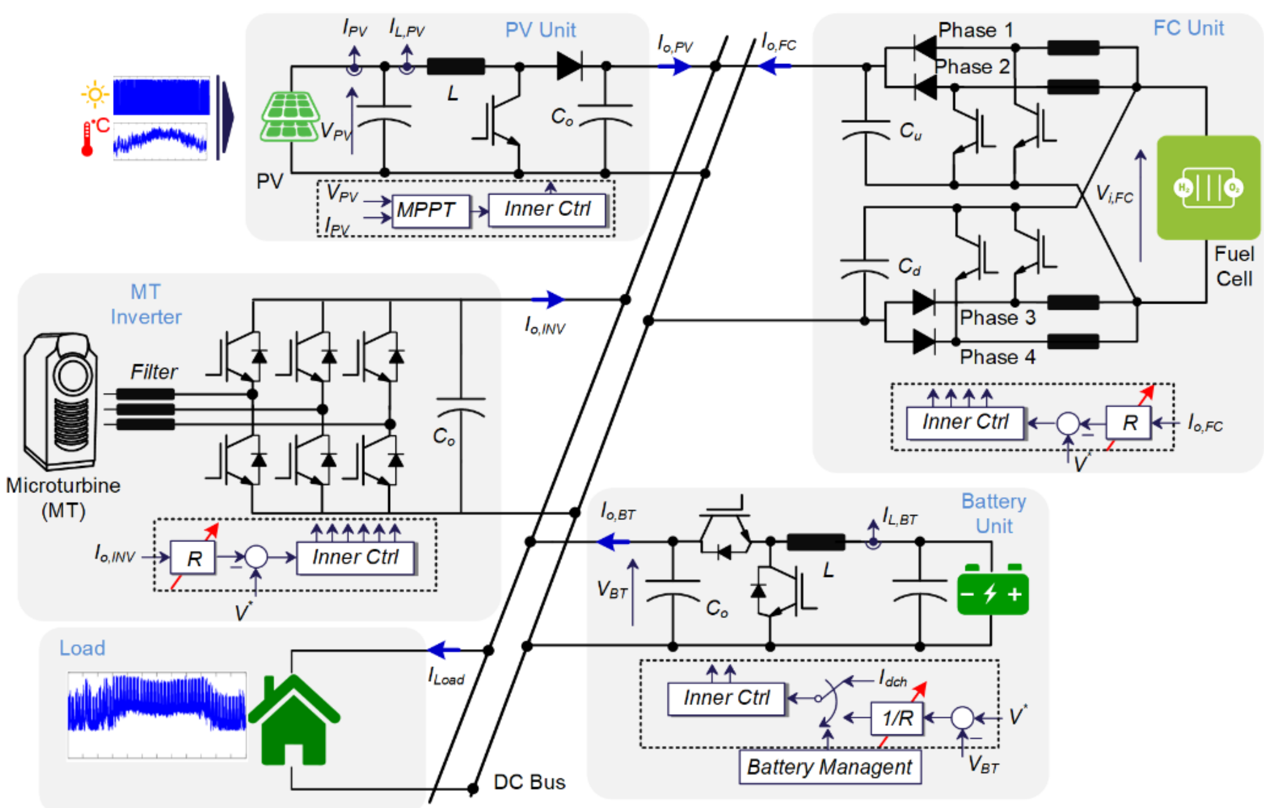

Fig. 3. Structure of a DC power electronic-based power system with different converter topologies and energy sources.

TABLE II POWER CONVERTER COMPONENT AND SPECIFICATIONS.

Converter Parameters	Microturbine (MT)	PV Converter	FC Converter	Battery Converter
Rated power	5 *kW*	5 *kW*	5 *kW*	5 *kW*
Switching frequency	20 *kHz*	20 *kHz*	20 *kHz*	20 *kHz*
DC Bus voltage	400 *V*	400 *V*	400 *V*	400 *V*
Input voltage	150 *Vac,* (50 *Hz*)	220 – 320 *Vdc*	72-110 *Vdc*	300-335 *Vdc*
Output capacitor	2×220 μF (C_o)	2×220 μF (C_o)	5×220 μF (C_u, C_d)	2×220 μF (C_o)
ESR per capacitor @ 100 Hz	0.41 Ω	0.35 Ω	0.24 Ω	0.41 Ω
Capacitor thermal resistance,	19.5 *K/W*	19.5 *K/W*	28 *K/W*	19.5 *K/W*
and time constant	10 *min*	10 *min*	10 *min*	10 *min*
DC inductor	-	1 *mH*	1 *mH*	1 *mH*
IGBT	IGB20N60H3	IGB10N60T	IGB15N60T	IGB15N60T
Diode	IDV15E65D2	IDV20E65D1	IDV20E65D1	IDV15E65D2
Battery capacity	-	-	-	2000 *Ah*

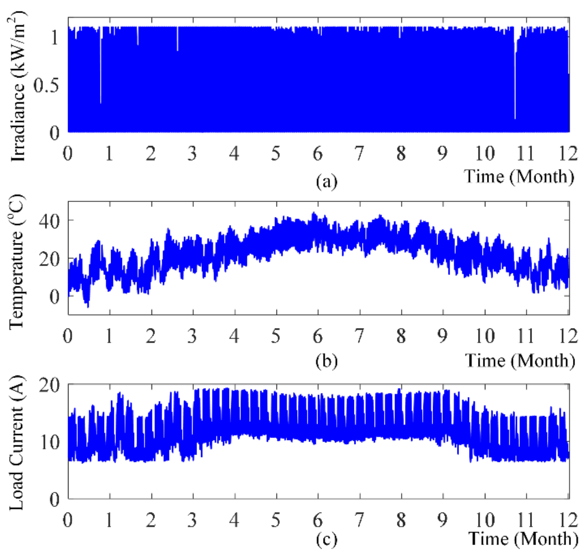

Fig. 4. Annual profiles: (a) solar irradiance, (b) ambient temperature, and (c) load profile (see Fig. 3).

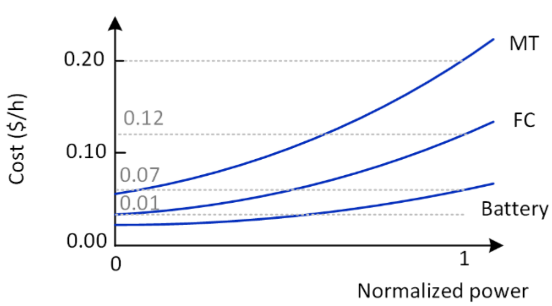

Fig. 5. Operational cost of different units shown in Fig. 3.

The converters reliability functions under the given mission profiles shown in Fig. 4 and energy management strategies is predicted using stress-strength analysis presented in [33]. Afterwards, the converters unavailability functions are obtained according to [34]. The unavailability of converters under three power sharing strategies is illustrated in Fig. 6. It is shown in Fig. 6(a and b) that by using a reliability-oriented load sharing approach compared to the conventional one the unavailability of FC and battery is decreased. Moreover, the unavailability of the MT is increased, which implies the shifting of the load of battery and FC to the MT. As a result, the system reliability measured by LOLE (loss of load expectation [35]) is decreased as shown in Fig. 7. LOLE shows the number of hours per year that the load cannot be supplied due to the failure of failure of any components, thus the lower LOLE indicates the higher system reliability. According to Fig. 7, if the standard level of LOLE to be considered as 8 h/y, then, the system reliable span – the period that the system stays reliable – is 16 years. This means the reliability-oriented approach extends the system reliable span by 4 years. Moreover, the operational costs of units are summarized in TABLE III. Using the reliability-oriented approach, increases the overall operational costs by 21% according to TABLE III.

The unavailability function of units using the proposed reliability/cost-based approach is shown in Fig. 6(c). The unavailability function of battery and FC is lower than the conventional approach shown in Fig. 6(a). Meanwhile, it is higher than the reliability-oriented technique shown in Fig. 6 (b). The overall system reliability measured by LOLE is improved compared to the conventional one as shown in Fig. 6. However, reliability enhancement compared to the reliability-oriented technique is limited. As shown in Fig. 6, the system becomes unreliable after 14 years using the proposed method. Moreover, the operational costs are given in TABLE III, where it is 6% higher than the conventional approach, while it is 15% lower than the reliability-oriented technique. This case study shows that there is a compromise between reliability and operational costs of units. The proposed reliability/cost-based approach provides a better reliability while minimizing the operational costs.

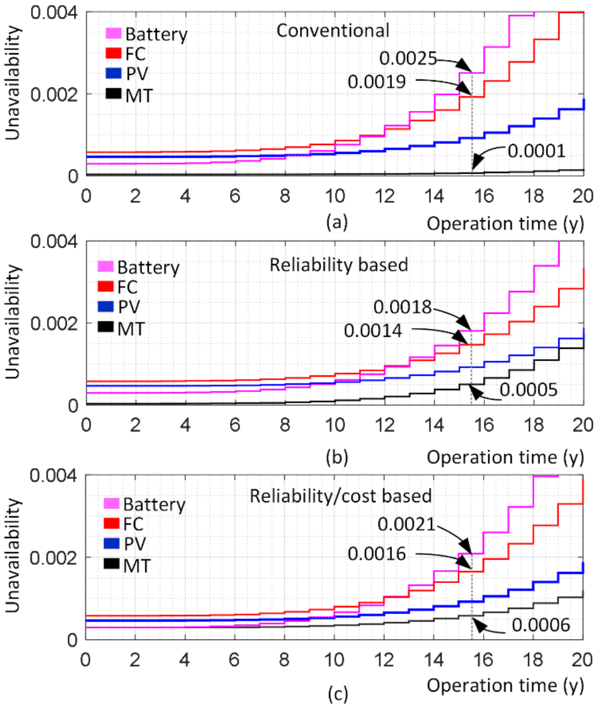

Fig. 6. Unavailability of converters due to wear-out failure under load sharing schemes of (a) conventional, (b) reliability-oriented and (c) reliability/cost-based.

These results for the 12th year of operation are presented in Fig. 8. The LOLE shows the system reliability in 12th year, where the lower LOLE shows a better reliability. Following Fig. 8, the LOLE is decreased by using the reliability/cost-based approach and the reliability-oriented approach respectively. Meanwhile, the operational costs are increased for the case of employing reliability/cost-based and reliability-oriented methods. Therefore, higher reliability demands for higher costs. However, the cost of reliability enhancement in more reliable conditions is higher than less reliable conditions. As shown in Fig. 8, improving the reliability by 2 h/y form conventional approach to the reliability/cost-based approach needs 6% of annual operation costs, while improving the reliability from reliability/cost-based approach to the reliability-oriented approach by 0.95 h/y demands for 15% of operation costs. While the reliability enhancement is almost halved, the corresponding costs are almost tripled. Therefore, it is of high importance to provide reliability worth-cost analysis to find an optimal point where the reliability is enhanced with minimizing the operational costs. This point is shown in Fig. 8, which is obtained by using reliability/cost-based power sharing approach.

Therefore, employing the proposed approach enhances the reliability of the system with respect to the operational costs of the units. Unlike the conventional power sharing approach for power electronic-based systems, the proposed approach takes into account the thermal damage of the units and their operational costs. Therefore, not only it prevents the overloading and over-stressing the units, but also it enhances the overall system reliability, and at the same time decreases the operational costs. This method can automatically provide

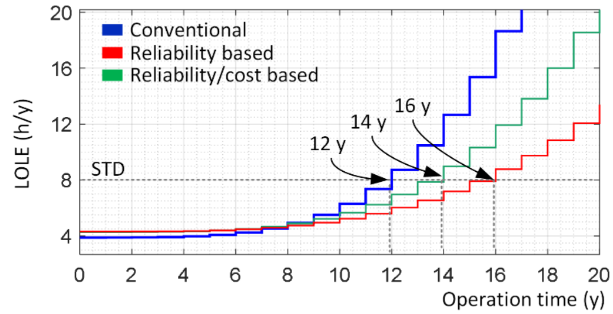

Fig. 7. Overall reliability (LOLE) of the microgrid shown in Fig. 3.

TABLE III ANNUAL OPERATIONAL COSTS ($/y).

Power Sharing Strategy	Conventional	Reliability oriented	Reliability/cost based
Fuel cell (FC)	1,100	830	955
Battery storage	530	430	485
Microturbine (MT)	1,235	2,215	1,590
Total	2,865	3,475(21%)	3,030(6%)

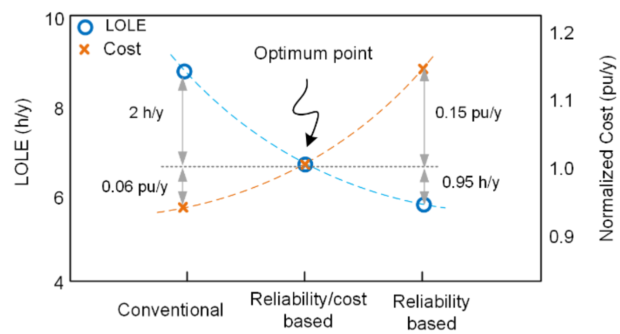

Fig. 8. Reliability cost-worth analysis, LOLE: loss of load expectation (reliability index), and the cost in per unit (pu) represents the operational costs normalized per 3,000 $.

operational planning services such as reliability services, economic dispatch, and autonomous operation to the islanded microgrids specially, thus enhancing self-organizing capability of power electronic systems.

IV. Conclusion

This paper has proposed a unified reliable and cost-effective power routing strategy for power electronic-based power systems. The proposed approach employs a droop control method, where the droop coefficients are proportional to the thermal damage and operational costs of corresponding energy sources. Therefore, not only it prevents the overloading and over-stressing sources, but it enhances also the overall system reliability, meanwhile decreasing the operational costs. The performance of the proposed approach was compared with the conventional and reliability-oriented power routing methods using simulations. According to the simulations, the conventional approach resulted in lower costs, while introducing higher LOLE, thus lower system reliability. On the other hand, the reliability-oriented approach introduces lower LOLE, i.e., better reliability, while having higher operational costs. Therefore, higher reliability demands for higher operational costs. On the other hand, the proposed approach improves the overall reliability by minimizing the operational costs. This is illustrated by simulations, where the reliable operation span, i.e., LOLE lower than 8 h/y, was limited to 12 years under the conventional power sharing approach. Meanwhile, the reliability-oriented power sharing extended the reliable span up to 16 year. This shows that the operational cost is increased by 21%. However, employing the proposed reliability/cost-based approach has enhanced the system reliable span to 14 years while the operational costs is increased by 6% compared to the conventional approach.

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