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Techno-economic Analysis of DC Microgrid and its Distributed Control Strategies with Fault Current Mitigation Technique for Power Sharing and Voltage Regulation

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Techno-economic Analysis of DC Microgrid and its Distributed Control Strategies with Fault Current Mitigation Technique for Power Sharing and Voltage Regulation

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DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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ABSTRACT

Recent research on DC systems revealed that DC microgrids can be an efficient, reliable and economical solution to avoid the inherent issues associated with AC power integration such as frequency control, harmonics and synchronization. One major concern of the DC microgrids with multiple converters is the control of power sharing, aiming to maintain the voltage profile, particularly during system disturbances. Under the worst scenarios, DC microgrid operation may be completely impacted if properly distributed control strategies are not considered with an effective protective approach to eliminate the fault currents. The ongoing studies presented in the area of DC microgrid control reflect its importance, however, the stability of an isolated DC microgrid in terms of power sharing and voltage regulation especially under fault conditions is not sufficiently addressed in the literature. In the first objective of this research, a framework has been proposed to assess the technical benefits of implementing either AC or DC distribution considering the existing AC infrastructure. Further, a Hybrid Optimization of Multiple Electric Renewables (HOMER) based analysis has been carried out to determine the most economical and optimal size of an isolated solar PV system with its energy storage to be connected either as an AC or DC microgrid. From the obtained outcomes of the above-mentioned framework, a distributed secondary control strategy has been developed in the second objective. This approach is based on average-voltage/average-current control and circulating current minimization for DC bus voltage regulation and maintaining power sharing under different scenarios. In that sense, an additional current feedback loop is introduced to modify the microgrid reference voltage during overload conditions to minimize the line voltage drop and distribution losses. Finally, to mitigate the vulnerability of isolated DC microgrid control due to fault conditions, a preventive scheme of controllable fault current limiter (C-FCL) has been designed in the third objective. The C-FCL acts in a coordinated manner with the implemented control of power sharing and voltage regulation. This research study was carried out using the HOMER optimizer and MATLAB/Simulink with small-scale experimental validation. The results show that applying DC voltage magnitude equal to the peak value of AC voltage reduces the power loss of DC microgrid up to half value compared to AC microgrid and the voltage drop in the distribution lines reduces by 29.3%. It is revealed that the proposed control strategy has better voltage regulation, and power sharing performance without any significant deviation imposed by variation in PV generation as well as load switching. Further, using the proposed C-FCL protective scheme can limit the fault current magnitudes for different fault locations, keeping the converters operating in a safe mode during fault conditions. The C-FCL increases the fault clearance time for the protection system providing more efficient and reliable operation of the DC microgrid.

Keywords: DC microgrids, techno-economic analysis, power sharing, fault current limitation

Pembangunan Strategi Pengendalian Teragih dengan Teknik Mitigasi Arus Kesalahan untuk Perkongsian Daya dan Peraturan Voltan dalam* DC *Mikrogrid

ABSTRAK

Penyelidikan dan kemajuan terkini dalam sistem DC menunjukkan bahawa mikrogrid DC dan pengedaran DC merupakan penyelesaian yang cekap, boleh dipercayai, dan ekonomik untuk mengelakkan masalah sistem kuasa AC seperti kawalan frekuensi, harmonik dan penyegerakan. Walau bagaimanapun, satu masalah utama mikrogrid DC dengan beberapa penukar adalah kawalan perkongsian kuasa, yang bertujuan untuk mengekalkan profil voltan terutamanya semasa gangguan sistem. Di dalam senario terburuk, operasi mikrogrid DC mungkin benar-benar terjejas jika strategi kawalan terdistribusi yang betul dan pendekatan perlindungan yang berkesan untuk menghilangkan arus kerosakan tidak dipertimbangkan. Kebanyakan kajian bidang kawalan mikrogrid DC yang dijalankan mencerminkan kepentingannya, walau bagaimanapun, kestabilan mikrokrid DC dari segi pembahagian kuasa, peraturan voltan dan batasan arus kerosakan tidak diberi perhatian yang cukup dalam literatur. Dalam objektif pertama penyelidikan ini, kerangka kerja untuk menilai manfaat teknikal dan kewangan dalam melaksanakan mikrogrid AC dan DC telah dicadangkan. Selanjutnya, tingkah laku dinamik mikrogrid AC dan DC telah dianalisis ketika setiap sistem mengalami gangguan seperti kesalahan litar pintas, dengan tujuan untuk menilai tindak balas sistem. Pada tahap berikutnya, analisis ekonomi telah dilakukan untuk menentukan ukuran optimum sistem PV suria yang disambungkan ke setiap microgrid AC atau DC dengan simpanan tenaganya, menurut data profil meteorologi dan muatan dari daerah terpencil terpilih di Sarawak (Malaysia). Dalam objektif kedua, strategi kawalan pengedaran sekunder telah dikembangkan untuk melancarkan voltan output dan mengekalkan pembahagian daya berdasarkan kawalan voltan rata-rata / arus-arus dan *pengurangan arus yang beredar. Oleh itu, gelung maklum balas arus tambahan diperkenalkan untuk mengubah voltan rujukan mikrogrid semasa keadaan beban yang berlebihan untuk meminimumkan penurunan voltan talian dan kehilangan kuasa. Untuk mengurangkan kesan peningkatan arus yang cepat pada pembahagian kuasa dan kawalan peraturan voltan semasa keadaan kerosakan, skema pencegahan pembatas arus kerosakan yang dapat dikawal (C-FCL) telah dirancang pada objektif ketiga dan diuji menggunakan konfigurasi mikrogrid cincin DC. C-FCL bertindak secara terkoordinasi dengan perlaksanaan algoritma pembahagian kuasa dan peraturan voltan. Kajian di atas dilakukan dengan menggunakan HOMER dan MATLAB / Simulink. Hasilnya menunjukkan bahawa penerapan voltan DC yang sama dengan nilai puncak bentuk gelombang AC boleh mengurangkan kehilangan kuasa mikrogrid DC hingga separuh nilai berbanding dengan mikrogrid AC dan penurunan pengedaran voltan berkurang sebanyak 29.3%. Ini menunjukkan bahawa strategi pengendalian yang dicadangkan mempunyai peraturan voltan dan prestasi perkongsian daya yang lebih baik di dalam semua kondisi beban. Di samping itu, C-FCL yang dicadangkan efektif dalam membatasi magnitud arus kesalahan di lokasi yang berlainan untuk mengurangkan kerentanan kawalan mikrogrid terhadap kesalahan sementara. Akhirnya, hasil yang diperoleh mengesahkan bahawa strategi kawalan yang dicadangkan dengan skema pencegahan arus kesalahan yang diselaraskan memberikan operasi mikrogrid DC yang lebih cekap dan boleh dipercayai.*

Kata kunci: *Mikrogrid DC, analisis tekno-ekonomi, perkongsian kuasa, had arus kesalahan*

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LIST OF ABBREVIATIONS

CCT	Critical Clearing Time
CERTS	Electric Reliability Technology Solutions
C-FCL	Controllable Fault Current Limiter
COE	Cost of Energy
CRF	Capital Recovery Factor
DG	Distributed Generation
DRES	Distributed Renewable Energy Sources
DRG	Distributed Renewable Generation
ESS	Energy Storage Systems
FCL	Fault current limiter
HOMER	Hybrid Optimization Model for Electric Renewable
HVDC	High-Voltage DC
LVDC	Low-Voltage DC
MTDC	Multi-Terminal DC
NPC	Net Present Cost
PCC	Point of Common Coupling
PQ	Power quality
PV	Photovoltaic
PWM	Pulse Width Modulation
RES	Renewable Energy Sources
SAA	Scaled Annual Average

CHAPTER 1

INTRODUCTION

1.1 Study Background

According to the ‘Energy trends: What’s the outlook for 2035’ report [1], global energy demand is expected to grow by nearly 40% of that in 2015. Most of the increase in energy demand is foreseen in the fast-growing and developing economies. The global energy demand in past decades was supplied by fossil fuels, however, due to price fluctuations, limited natural resources and the impact of CO_2 emissions, the focus on developing renewable energies as alternatives to fossil fuels has grown rapidly throughout the world. The main reason behind this is the rapid growth of competitive supply markets and developments of low-cost, low-power distributed generation (DG) technologies compared to the high cost of transmission and distribution networks especially in rural and remote areas with low power demands. Distributed Renewable Generation (DRG) plays a key role in providing services such as electrification, modern communication to facilitate education, improved health and other socio-economic activities with co-benefits such as reducing air pollution and positive effects on income growth in rural areas where utility grid supply is difficult and expensive [2].

Globally, an approximate 6.5% annual growth in renewable energy production is expected over the next 20 years. The share of renewable energy sources (RES) in primary energy production is expected to grow from 3% in 2015 to 8% by the end of 2035. During the past decades, approximately 145 countries adopted policies that support renewable energy technologies. At the present stage, 10 Terawatts (TW) of electrical power is consumed throughout the world annually, and this consumption is expected to reach 30 TW by 2050. Global climate reports indicate that greenhouse gas emissions must be reduced to 80% of their 1990 levels to prevent global warming. Therefore, 20 TW of clean, renewable energy is required to level out the hazardous gases in the atmosphere [1], [3], [4].

The largest growth in renewable power generation capacity, 178 Gigawatt (GW), was recorded in 2017, comprising almost 70% of the net additions to worldwide renewable power generating capacity for the year. Meanwhile, total global renewable power capacity reached 2,195 GW. Approximately 10.3 million people were employed (directly and indirectly) by the renewable energy sector, and new investments of approximately US$280 billion were made globally. Strong growth in renewable energy was observed in the power sector. However, current advances are uneven across sectors, such as transportation, heating and cooling, which comprise approximately 80% of net global energy demand, because policymakers focused on providing electricity access, especially in remote and rural areas [5]. Solar photovoltaic (PV) and wind power capacity installations account for approximately 56% and 29% of energy generation, respectively, while small hydropower, below 50 megawatts, contributed 11% of renewable power capacity added in 2017. Figure 1.1 (a) shows the percentage of RES participation in total global renewable power generation capacity at the end of 2017, while (b) shows the participation of new installations in 2017. Figure 1.1(b) indicates that solar PV and wind power installations were remarkable in the power sector. Therefore, future research targeted these sources. Nearly 99 GW of solar power was added globally, and total solar capacity worldwide increased to 402 GW.

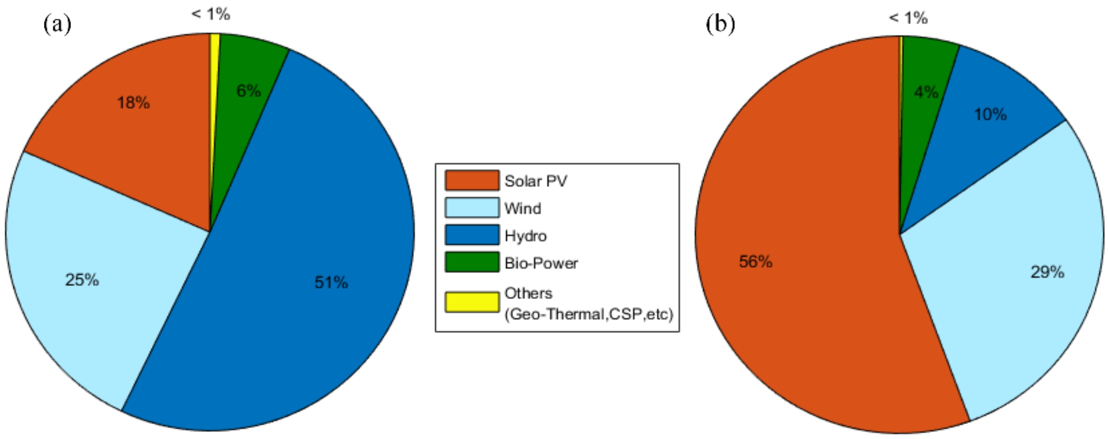

Figure 1.1: Total Installed Renewable Power Capacity Worldwide (a) At the end of 2017; (b) New Installation in 2017 [5]

Asian markets continue to dominate solar power addition for the fifth consecutive year, with China holding the first position in the top 10 rankings for solar power addition, followed by the United States, India, Japan, Turkey, Germany, Australia, South Korea, United Kingdom and Brazil [5], [6]. Table 1.1 shows the top-ranked countries in total and added solar power capacities at the end of 2017.

Table 1.1: Top10 Countries for Solar Power Capacity Installation in 2017 [5], [6]

No	Total Solar Power Generating Capacity Installed in GW at the end of 2017		The Newly Installed Solar Power Generating Capacity (GW) in 2017	
1	China	131	China	53
2	USA	51	USA	10.6
3	Japan	49	India	9.1
4	Germany	42	Japan	7

Table 1.1 continued

5	Italy	19.7	Turkey	2.6
6	India	18.3	Germany	1.8
7	United Kingdom	12.7	Australia	1.25
8	France	8	South Korea	1.2
9	Australia	7.2	United Kingdom	0.9
10	Spain	5.6	Brazil	0.9
	Total solar power capacity worldwide	402	Total added solar power capacity in 2017	99

Wind power generation has also become a clean option in an increasing number of markets worldwide. The cumulative worldwide installed wind power generation capacity at the end of 2017 was 539 GW. The global wind power growth observed over the last five years is as follows: 52 GW in 2017, 54.64 GW in 2016, 63.33 GW in 2015, 51.68 GW in 2014 and 36.02 GW in 2013. Commercial wind activity was observed in more than 80 countries, while 26 countries generated more than 1 GW of wind power. Asian countries (China, India and Japan) were the largest markets for wind power capacity installation in 2017, accounting for approximately 47% of total new capacity installations worldwide, followed by the European Union with 32% and North America with 15%. At the end of 2017, China led the world in both total and added wind power capacity (188.23 GW), leaving the United States behind (89.08 GW). The top 10 countries in total wind energy generation capacity were Germany, India, Spain, the United Kingdom, France, Brazil, Canada and Italy. The top 10 countries in capacity addition in 2017 were China, the United States, Germany, India, United Kingdom, Brazil, France, Canada, Italy and Spain [5], [6]. Table 1.2 summarizes the total and added wind power capacity data from the top 10 countries at the end of 2017.

Table 1.2: Top10 Countries for Wind Power Capacity Installations in 2017 [5], [6]

No	**Total Wind Power Generation Capacity at the end of 2017 in GW**		**The Newly Installations of Wind Power Generation (GW) in 2017**	
1	China	188.23	China	19.54
2	United States	89.08	United States	6.90
3	Germany	56.13	Germany	6.11
4	India	32.85	India	4.18
5	Spain	23.17	United Kingdom	3.84
6	United Kingdom	18.87	Brazil	2.02
7	France	13.76	France	1.69
8	Brazil	12.76	South Africa	0.62
9	Canada	12.24	Poland	0.61
10	Italy	9.48	Finland	0.57
	Total wind power capacity worldwide	539	Wind power capacity additions in 2017	52

1.2 Microgrid Concept

Although utility grid propagation or extension is the first option for electrification and should be economical when compared to other off-grid options, however, it is a challenge to integrate distributed renewable energy sources (DRES) such as PV systems, wind turbines, fuel cells, micro-hydro and energy storage systems (ESS) directly into the utility grids because of their intermittence and uncertainty. The cost of supplying grid-based electricity to remote areas with low power demands becomes uneconomical, in such situations, stand-alone renewable energy microgrids based on smart metering and control become the most viable option for sustainable development. In 1999, the Consortium for Electric Reliability Technology Solutions (CERTS) originated the concept of the modern grid-connected microgrid system. CERTS define a microgrid as a localized group of controllable DRES and loads that present itself as a single customer or a small generator to the existing utility grid, which can disconnect and independently operate according to the physical and/or economic conditions. The microgrid concept has proven itself as one of the most practical solutions to utilize DRES and can eliminate the perceived challenges of integration with improved reliability in the case of natural disasters, physical/cyber-attacks, and cascading power failures with decentralized and autonomous control solutions [7]. However, all these benefits are dependent on efficient coordination within the microgrid as well as with the utility grid. Any discoordination can lead to critical problems such as islanding and protection issues. Therefore, the intelligent power grid/smart grid with real-time monitoring and optimization needs to be developed to ensure a more reliable power delivery to the end-user. The smart grid concept integrates communication networks with power systems to provide real-time monitoring (smart metering) and control of power system components. According to the US National Institute of Standards and Technology (NIST), a smart grid is defined as “a transition process from the existing power system to the future Information and Communication Technologies (ICT) based power system”. A smart grid is capable of bidirectional power flow and has full control over the grid components using