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*Corresponding author: Rukia J. Mwifunyi, Computer Science and Engineering, University of Dar es Salaam College of Information and Communication Technologies, Tanzania
E-mail: rukiahilda@gmail.com

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Kun Chen, Wuhan University of Technology, Wuhan, China

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Distributed approach in fault localisation and service restoration: State-of-the-Art and future direction

Rukia J. Mwifunyi^{1*}, Mussa M. Kissaka² and Nerey H. Mvungi¹

Abstract: This paper presents a survey of recent development in Fault Localisation and Service Restoration (FLSR) following electrical disturbance in Power Distribution Systems (PDS) based on distributed approaches. Distributed approaches have been found to fit well in the distribution systems as they have more than one decision-making component, and data processing can be done in parallel in individual units that makes it faster and requires less processing capabilities centrally. Recently reported distributed approaches have been studied and analysed. With ever-growing integration of the renewable distributed generation (DG) into the distribution systems, it has been realised that, the uncertainty nature of both load demand and DG need to be considered in the service restoration problems for improved efficiency. Consideration of uncertainty nature of the renewable generation and load demands in the distributed FLSR result into the increased restored customers as well as avoiding overloading and underloading after restoration. The paper starts with a general overview of the Multi Agent Systems (MAS) as the distributed control approach and approaches for forecasting load demand and DG power and then discusses different approaches used for FLSR in PDS by showing their strengths and limitations. The review is concluded by giving future research directions.

ABOUT THE AUTHOR



Rukia J. Mwifunyi

Rukia J. Mwifunyi received bachelor and master degrees in Telecommunication Engineering from the University of Dar es Salaam, in 2010 and 2013, respectively. She joined University of Dodoma in the College of Informatics and Virtual education as a Tutorial assistant in 2011 and became an assistant lecturer in 2013. She is currently pursuing PhD in Computer and IT System engineering at University of Dar es Salaam. Her current research interests include Multi-agent systems, Smart Grid, Internet of Things, Self-healing systems and Optimisation.

PUBLIC INTEREST STATEMENT

Fault localisation and restoring services to customers after the occurrence of fault need to be accomplished as soon as possible to reduce unexpected losses to customers and utility. Distribution systems are evolving towards self-healing systems, which can quickly recognise the faulty area and restore power to customers. The high penetration level of renewable generations and unpredictability of load contribute significantly to the increased uncertainty in the distribution systems during service restoration process. Both centralised and distributed approaches were developed to solve the restoration problem. Distributed approaches based on agent technologies have emerged as the vital tool in controlling complex networks. This work reviews distributed control approaches for the FLSR in distribution networks through in-depth analysis on the techniques used in

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1. Introduction

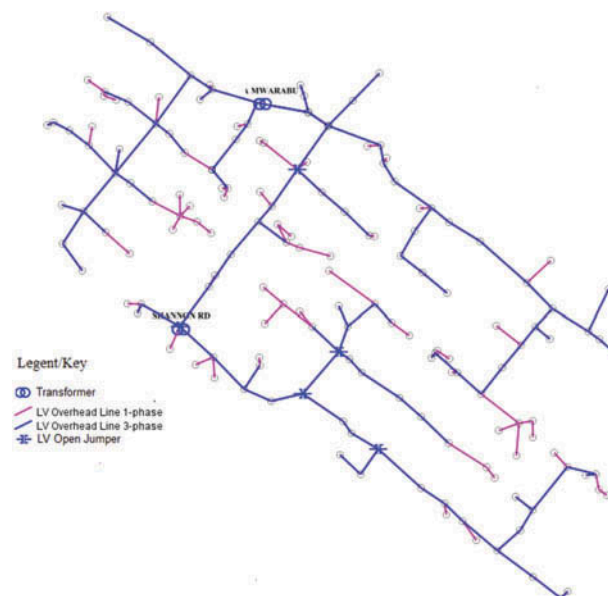
Demand of electric power, the size and complexity of modern power systems are increasing rapidly resulting into increased likelihood of occurrence of faults and sizes of areas affected by faults. As a result, the process of tracing, locating and fixing faults is time consuming and challenging (Ferreira, Gazzana, Bretas, & Netto, 2012). The durations of faults clearance directly affect safety, reliability, energy quality and overall satisfaction of customers, which, in turn, have a great effect on the revenue earned by electricity supply companies (Kumar, Das, & Sharma, 2006b).

The need for finding efficient ways of detecting, isolating the affected areas and quickly restoring unaffected areas have increased significantly (Ghorban, Choudhry, & Feliachi, 2013). Earlier on, due to small sizes of electrical power distribution networks, strategies and guidelines were limited to operating companies, i.e. no uniform guidelines to restore the system were established (Latare, Bhat, & Srivastava, 2017).

Given growing interest in smart grid technologies and applications, self-healing is becoming a highly important research area (Al & Al-Muhaini, 2018). Distribution systems are evolving towards self-healing systems, which can quickly recognise and isolate faulted components and restore power to unaffected customers with little or no human intervention. A self-healing mechanism through enhanced fault localisation and supply restoration can substantially reduce the outage times and improve the continuity of supply (Bahmanyar et al., 2016).

Considering the presence of multiple laterals and sub-laterals tapped from the main feeder at different locations in the Power Distribution Systems (PDS) as seen in Figure 1 and time varying unbalanced load profiles, uncertain renewable Distributed Generation (DG) connected in PDS, fault locating and service restoration are challenging tasks (Ferreira et al., 2012). Significant work has been done to enhance fault localisation and service restoration (FLSR) in PDS. Methods for locating

Figure 1. One Line Diagram for Power Distribution Network.



fault and service restoration in PDS comprises both centralised and distributed approaches. Centralised approaches for fault localisation can be categorised into automated outage mapping, impedance-based method (Gabr, Ibrahim, Ahmed, & Gilany, 2017), travelling wave-based method, voltage sag-based method (Jamali, Bahmanyar, & Bompard, 2017) and knowledge-based method (Aslan & Yagan, 2016). However, most of them perform efficiently in transmission lines where the lines are homogeneous and there are no laterals. Similarly, these methods have also been implemented in the Medium Voltage (MV) network but with some improvement to accommodate the distribution network nature though multiple location estimations problem and time varying load modelling still need to be investigated (Bahmanyar, Jamali, Estebarsari, & Bompard, 2017).

Centralised approaches for solving service restoration optimisation problem including heuristic methods (Yu et al., 1992), expert systems, fuzzy reasoning (Hsu & Kuo, 1994), soft computing and mathematical programming have been proposed in literature. Centralised approaches have access to all network data and guarantee for the optimal solution. However, they rely on the centralised controller for decision making, which do not fit well in large complex networks (Solanki, Khushalani, & Schulz, 2007).

With ever-increasing size and complexities of electrical distribution networks, it is very expensive, risky and time consuming to still depend on centralised control approaches. The rapid advancement of computer science and telecommunication technologies invented distributed intelligence applications, as an alternate solution, which have developed solutions based on Multi-Agent Systems (MAS) (Hossein Sekhavatmanesh & Cherkaoui, 2018). In distributed control approaches, there are more than one decision-making component and data processing can be done in parallel in individual units that makes it faster and requires less processing capabilities in which have been realised that can work well in complex networks. Moreover, less communication capabilities are required in distributed control methods since there is no single central unit that is responsible for all communications. MAS has been used in fault localisation (Ghorban et al., 2013) and service restoration (Chouhan, Mohammadi, Feliachi, Solanki, & Choudhry, 2016; Zidan & El-Saadany, 2012) and has shown promising results.

Nowadays, the distribution systems are becoming active as the result of penetration of the renewable DGs, due to its benefits of increased capacity, reliability and power quality during service restoration (Sekhavatmanesh, Nick, Paolone, & Cherkaoui, 2018; Zidan et al., 2017). Renewable DGs are also beneficial because they are pollution free and have low implementation costs. However, the power generated by renewable DG is not predictable in nature with higher variations depending on the environmental conditions (Zidan & El-Saadany, 2013).

Also, it is apparent that the capacity of supplying unserved loads during restoration requires knowledge of the load (Donde, Wang, Yang, & Stoupis, 2010). The load demand varies with the weather conditions, time of the day and nature of customers. The stochastic nature of both load demand and renewable DGs needs to be considered in the restoration problem for effectively utilisation of available capacity and avoiding unnecessary loss of sensitive loads (Zidan & El-Saadany, 2013). Most of the existing studies in service restoration used either pre-fault values or peak values of load demand and power from renewable generations resulting to overloading or underloading of power distribution networks (Hossein Sekhavatmanesh & Cherkaoui, 2018). Accurate forecasting methods of both load consumption pattern and renewable energy resources are needed for balancing demand and supply (Moradzaeh & Khaffafi, 2017) during service restoration in the adaptive distributed control approaches. Different techniques including the statistical (Sharma, Srinivasan, & Trivedi, 2016), artificial neural networks (Sharma, Trivedi, & Srinivasan, 2018) and hybrid method (Dou, An, & Yue, 2016) have been used in forecasting load demand and power for renewable distributed energy sources. This work aimed at reviewing the distributed control approaches for the FLSR in distribution networks, explore their strengths and limitations and giving future research directions. Thorough analysis

on the techniques used in the consideration of the stochastic nature of load demand and renewable DGs has also been conducted.

2. Materials and methods

This work adopts systematic review methodology in which the scientific text relies on critical analysis of the previous published materials and data. Library and databases search were used to identify the relevant published studies for review. Some of these libraries and databases are IEEE Xplore, Elsevier, ACM, Scopus, ScienceDirect, Web of Science, Energies and others. Keywords used to search relevant articles were Fault localisation, Service Restoration, Self-healing, Multi-agent Systems, Distributed Control and Load Forecasting. A total 309 studies were obtained through screening titles and abstracts. About 208 studies were removed from the list based on the initial criteria set for getting relevant articles to the study, these criteria are: the study should at least be conducted in electrical distribution network and considered either fault localisation and/or service restoration. The remaining 101 papers were reviewed by screening full papers, resulting to elimination of 30 papers and adding 18 extra resources obtained from references. Finally, a total of 89 papers were then reviewed critically and then other more criteria were added like the consideration of the load variation and use of multiagent systems for scrutinising studies which answer directly the research objective. Only 21 papers remained for in-depth qualitative synthesis and were used to construct the systematic review table. The summary of the research methodology adopted is presented in Figure 2.

3. General concepts

3.1. Multi-agent systems

A Multi-agent system is delineated as a collection of autonomous agents which can perform tasks based on goals in an environment that can be difficult to be defined analytically (Habib, Youssef, Cintuglu, & Mohammed, 2016). Agents can be hardware or software units with high level of abstraction, occupant in a given environment, with the ability to interpret data and run autonomous actions that change the environment state as seen in Figure 3 (Latare et al., 2017; Solanki et al., 2007). Agents have properties such as autonomy, proactivity, reactivity and sociability

Figure 2. Flowchart for Research Methodology.

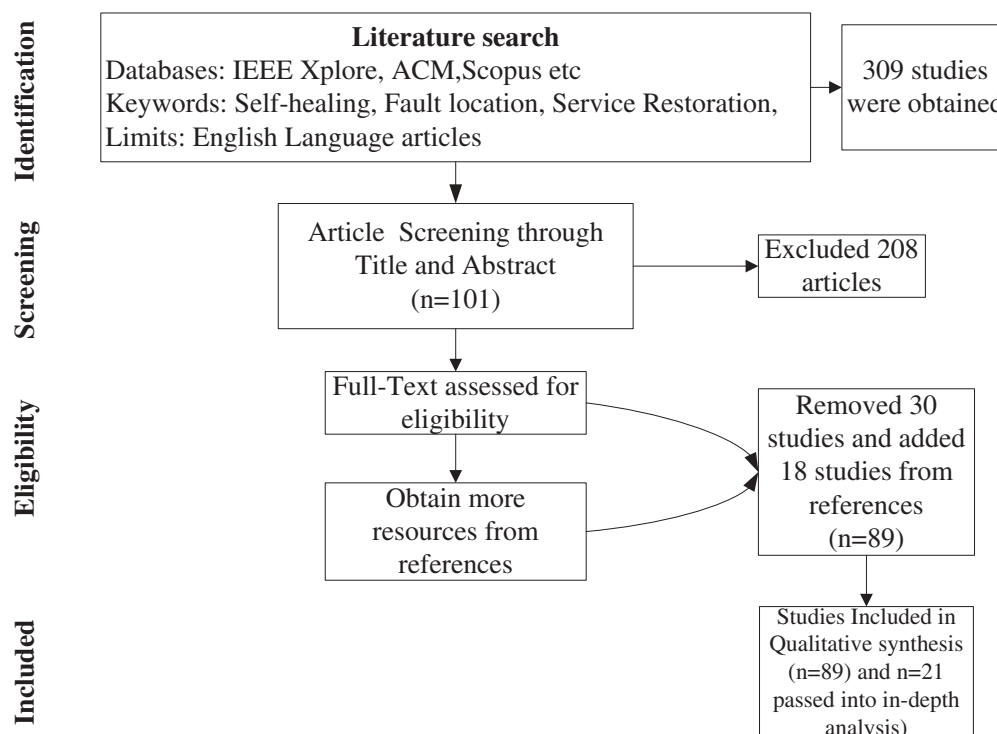
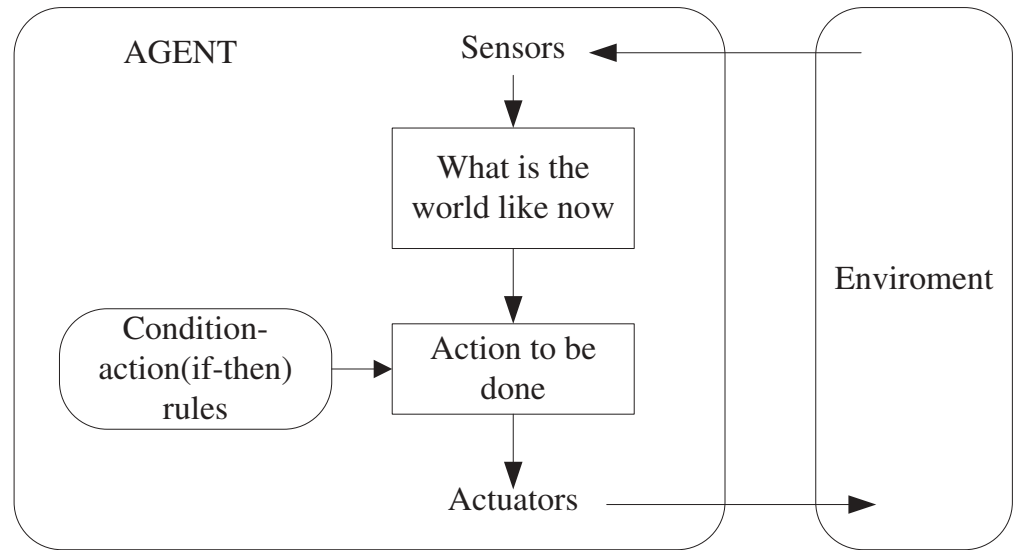


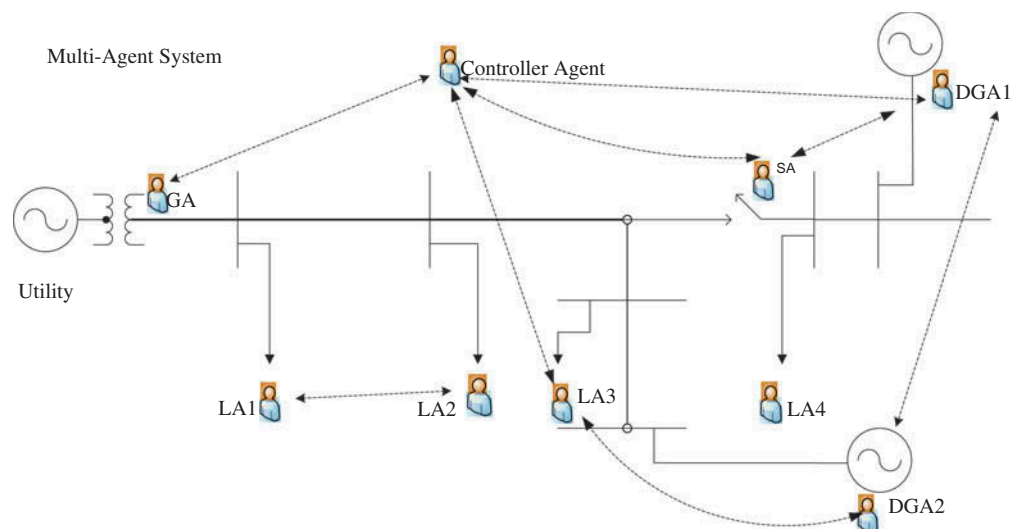
Figure 3. Schematic Diagram for an Agent.



(Sampaio, Melo, Leão, Barroso, & Bezerra, 2016). The autonomous nature of multi-agent system has attracted the applicability in different control systems including power systems restoration and protection. Figure 4 shows an example of Multiagent system for power distribution system restoration with five types of agents namely: Controller Agent, Load Agent (LA), DG Agent (DGA), Switch Agent (SA) and Grid Agent (GA). Dotted lines with double arrow show the communication between agents. The overall operation of these agents is based on the designed MAS architecture which can be centralised, distributed or hierarchical architecture.

In multi-agent systems, all agents need to coordinate their actions and behaviours so as to achieve their individual targets as well as work towards a common goal of the entire system which is commonly known as multi agent coordination. However, a problem arises when the number of agents within a system is very large and the constant exchange of information between the agents for a certain degree of good cooperation is limited. Interestingly, the agents are able to learn from their actions and behaviours in a systematic manner which is achieved through learning algorithms.

Figure 4. Multi-Agent System.



Reinforcement Learning (RL) has been chosen as the optimal learning algorithm in MAS (Menon, Menon, Srinivasan, & Jain, 2014). There have been tremendous advances by applying machine learning in agent technologies making it possible for an intelligent agent to adjust its behaviours based on the growing knowledge base. By applying RL algorithms, a control agent can select its actions in a dynamic environment while transferring to new states in an optimal way (Jin & Ma, 2017). In recent studies, the incorporation of the RL in the MAS has been found as a way of enhancing decision making as it helps to coordinate agents for getting global optimal solutions. Various studies have realised the use MAS-based RL into different applications in power system domains including reactive power control, adaptive protection coordination, microgrid control, market forecasting and restorative problems.

3.2. Uncertainty nature of load and DGs

The high penetration level of renewable DGs and the unpredictability of load contribute significantly to the increasing uncertainty in the distribution systems (Dou et al., 2016; Foruzan, Soh, & Asgarpour, 2018). The uncertainty nature can be catered through the use of effective and accurate forecasting mechanisms. Therefore, to develop an effective supply restoration strategy, an accurate forecast technique is essential (Sharma et al., 2016). Load forecasting can be categorised into very short time forecasting (within minutes), short time forecasting (within minutes and days) (Chen et al., 2018), medium time forecasting (up to 6 months) and long-term forecasting (up to years). Service restoration period can take minutes to days depending on the automation level of the distribution network, then the short-term forecasting is optimal for service restoration problems. Different approaches have been presented for short-term forecasting including statistical-based approaches, autoregressive models, artificial intelligence methods and hybrid approaches (Silva, Silva, Lisboa, Vieira, & Saldanha, 2018). Support vector regression has also been used in short-term forecasting of the load demand in power systems (Jiang, Ding, & Zhang, 2018). Among these approaches, artificial intelligence methods based on neural networks have been found to work well in applications containing variables with non-linear relationship (Azadeh, Ghadrei, & Nokhandan, 2009). However, it has limited accuracy as the number of variables increases, resulting in the increase in number of hidden layers which has over fitting effect (Chen et al., 2018). Deep Neural networks have been devised as a solution for improved accuracy in short-term forecasting (Ouyang, He, Li, Sun, & Baek, 2017).

Some studies, (Sharma et al., 2016) have considered the uncertainties of load and DG in MAS-based service restoration using statistical models and neural networks. Significant improvement in the utilisation of available capacity has been shown.

4. FLSR approaches

Most of the existing studies have considered FLSR separately, the advent of the smart grid has triggered researchers to study the complete problem (Ghorban, Choudhry, & Feliachi, 2016; Habib, Youssef, Cintuglu, & Mohammed, 2017) combining FLSR to comply with smart grid standards. Both centralised and distributed approaches have been devised in these two self-healing stages as discussed in the following sections.

4.1. Fault location approaches

Fault-location schemes with high-accuracy enable reduction of costs and time for the supply restoration (Pereira, Da Silva, Kezunovic, & Mantovani, 2009). In the literature, various methods for fault location detection in transmission and distribution lines have been proposed and deployed. These techniques include: automated outage mapping, impedance-based methods, travelling waves, knowledge-based methods, voltage sag measurements (Majidi, Arabali, & Etezadi-Amoli, 2015) and Multi-agent systems (Deshpande, 2015; Ghorban et al., 2013).

The travelling wave method in multi-branch distribution network is greatly influenced by the reflected wave, and it is susceptible to line type and wiring (Bahmanyar et al., 2017). The impedance-based method uses voltage and current measurements to find the faulted location and results to multiple estimations once used in distribution networks (Majidi et al., 2015). Voltage

sag method is not suitable for traditional distribution networks, as it requires extensive measurements to provide accurate results. Outage mapping require extensive amount of data though is very cheap. Knowledge-based methods require retraining once network topology changes (Bahmanyar et al., 2017). Moreover, integrated methods have been devised as the solution to multiple location estimation problem induced by impedance-based method and to overcome limitations of other methods.

Fault location identification using voltage and current measurements at substations was proposed in (Girgis, Fallon, & Lubkeman, 1993; Zhu, Lubkeman, & Girgis, 1997) and (Lee et al., 2004). A generalised non iterative impedance-based method was further proposed in (Gabr et al., 2017). A hybrid method using impedance and travelling wave-based method for locating faults in MV PDS using measurements at substation only was proposed in (Gazzana et al., 2014). Unbalanced operation, intermediate loads, laterals and time varying load profiles was taken into account. However, constants impedance load modelling was used which is far from reality. The method based on measurements at substation and along feeder was proposed in (Trindade, Freitas, & Vieira, 2014). The method based on smart feeder meters with voltage sag monitoring capability combined with outage mapping to reduce the search space and the chances of multiple estimation. However, the optimal placement of feeder meters and consideration of distributed generators were not studied. The study was extended by (Trindade & Freitas, 2016) who proposed that, once the meters are installed at the end of branch they give more accurate results. Another study for decreasing the multiple estimations associated with impedance-based method was done by (Estebasari, Pons, & Bompard, 2016) in which a hybrid solution was proposed, which includes impedance-based and voltage sag methods. Results have been presented only for single phase to ground fault without DG integration.

The aforementioned techniques for fault localisation are centralised as they depend on the central controllers that trigger the location algorithm after fault detection. Some of the methods try to locate the exact fault location and others just locate the faulty area. Recently, with the development of digital sensors and communications, researchers have devised Multi-agent technique which is distributed in nature for enhancing fault localisation and isolation process. Multi-agent system design with distributed intelligence for fault localisation and isolation in MV PDS with presence of DGs was studied by (Deshpande, 2015; Ghorban et al., 2013). MAS-based approaches mostly focus on fault area localisation and not pinpointing the exact location. There is still need for more research on establishing efficient fault location method in MAS-based systems for pinpointing exact location.

4.2. Service restoration approaches

The service restoration process needs to be performed within a short period so as to reduce outage time and its impacts. It is also required to maximise the number of restored customers, minimise the number of switching operations and reduce power losses (Ibrahim, Mostafa, Salama, El-Shatshat, & Shaban, 2018; Sekhavatmanesh & Cherkaoui, 2017) as stated by expressions (i–iii) while meeting several constraints including voltage and current limits. Due to the aforementioned requirements, the service restoration problem is formulated as a multi-objective, multi-constrained, and combinatorial problem. A number of techniques have been devised to solve this problem including centralised and decentralised techniques.

$$\max \sum_{i=1}^N w_i * L_i * y_i \quad (i)$$

$$\min \sum_{j=1}^{N_s} |x_j - x_{jo}| \quad (ii)$$

$$\min \sum_{i=1}^N I_i^2 R_i^2 \quad (iii)$$

Where L_i is the load at bus i , y_i : status of the load at the bus i , w_i : priority level of the load at bus i , x_j : status of j th switch in restored network, x_{j0} : status of j th switches immediately after network has been isolated, N : total number of buses, N_s : total number of switches, I_i : current in i th bus and R_i : resistance of i th bus.

4.2.1. Centralised approaches for service restoration

In a centralised control scheme, the measurement signals from distribution networks are sent to a centralised controller for processing, storage, decision making and visualisations. Centralised control approaches have access to all network data and are able to find the global optimal solutions. A number of algorithms have been devised for solving service restoration problem including Genetic Algorithm (GA), Simulated Annealing (SA), Particle Swarm Optimisation (PSO), Mixed Integer Linear Programming (MILP) and Anti-Colony (Campos, Figueroa, Oyarzun, & Baeza, 2018; Latare et al., 2017).

GA for generating a service restoration procedure for restoring as much load as possible in the out-of-service area have been proposed by, (Luan, Irving, & Daniel, 2002) and (Kumar, Das, & Sharma, 2006a). GA was considered due to its ability to find global optimisation solutions and its high suitability for parallel computing. The authors in (Fukuyama & Chiang, 1995) formulated the restoration problem without load shedding where the process terminates if full restoration cannot be served. In (Luan et al., 2002), load shedding was considered when total demand cannot be supplied during restoration process. Further extensions were proposed by (Kumar et al., 2006a) who considered both manual and remote-controlled switches and priority customers. However, the multi-objective function was converted to single objective using weighting factors that vary with network and load variability was not considered.

The work done by (Hsiao, Chien, & Member, 2000), presented a combination of fuzzy logic and GA method to solve the service restoration problem by retaining multi-objective nature. The problem formulation considered five objective functions which were modelled with fuzzy sets to evaluate their imprecise nature, and then the optimisation problem solved by GA. However, the parameters of the fuzzy set need to be tuned to every network for satisfactory performance. Requirements of weighting factors, which are network dependent for the conversion of a multi-objective optimisation problem into an equivalent single objective function have also been solved by non-dominated sorting genetic algorithm-II (NSGA-II) proposed by (Kumar, Das, & Sharma, 2008). In this work, various practical operation issues for distribution system, such as the presence of priority customers, remotely controlled, as well as manually controlled switches, etc. have also been considered, which were not considered in (Kumar et al., 2006b). However, cases for limited capacity of substation, load demand variation and inclusion of DG units have not been considered.

GA for SR was also studied by (Zidan & El-Saadany, 2013) and (Zidan & El-Saadany, 2015). The work done by (Zidan & El-Saadany, 2015), proposed a service restoration plan for distribution network incorporating customers' reliability requirement and interruption features. It has been observed that apart from the load variation which was studied by (Zidan & El-Saadany, 2013), the restoration plan is also affected by customer load types and sizes, time of occurrence, frequency of outage and outage duration.

Linear Integer Programming (LIP) has also been found as an efficient method for solving service restoration problem due to its ability of achieving global optima solution. In (Al & Al-Muhaini, 2018), a self-healing optimisation strategy for smart grids was proposed. The proposed self-healing strategy considered key aspects of the smart grid including controllable loads, Demand Side Management (DSM) customers, DG units, and load priorities. LIP was also used to solve restoration problem in (Chen, Chen, Wang, & Butler-Purry, 2018), in which a sequential SR algorithm was proposed which can be used in unbalanced distribution network with DGs. Moreover, LIP was also used by (Xu, Liu, Schneider, Tuffner, & Ton, 2018) who proposed a resiliency-based methodology that uses micro-grids to restore critical loads on distribution feeders after a major disaster. Stability constraints of

micro-grids have also been considered. However, studies didn't consider the impact of stochastic nature of load demand and DGs. Linear integer program for solving restoration problem has also been proposed by (Gao, Chen, Xu, & Liu, 2016) who incorporated uncertainties induced by intermittent energy source, though the dynamic constraints of MGs were not considered.

Heuristic search method has also been used in service restoration. (Kleinberg, Miu, & Chiang, 2009) and (Kleinberg, Miu, & Chiang, 2011) used a ranking-based heuristic search algorithm to solve the restoration problem. In these studies, load curtailment through direct load control was considered in case full restoration for out of service loads is not manageable or for reduction of switching operations. These studies did not consider the variability of load during restoration process resulting to unnecessary load shedding. The heuristic approach for service restoration in Secondary Distribution Network (SDN) was further developed in (Xu et al., 2017). The restoration method incorporated limits on DG capacity, operational limits and dynamic constraints. However, it was assumed that hierarchical control infrastructure is available and there is a central controller for controlling DGs and loads in the SDN, which may be invalid in practice. Moreover, the variation in load demands and uncertainty in DGs were not considered.

A PSO method has also been used in (Abdelaziz, Mekhamer, Badr, & Mohamed, 2009; Wu, Tsai, & Hsu, 2007) to solve the optimisation problem. PSO is a population-based evolutionary technique that has the ability to escape from local optima.

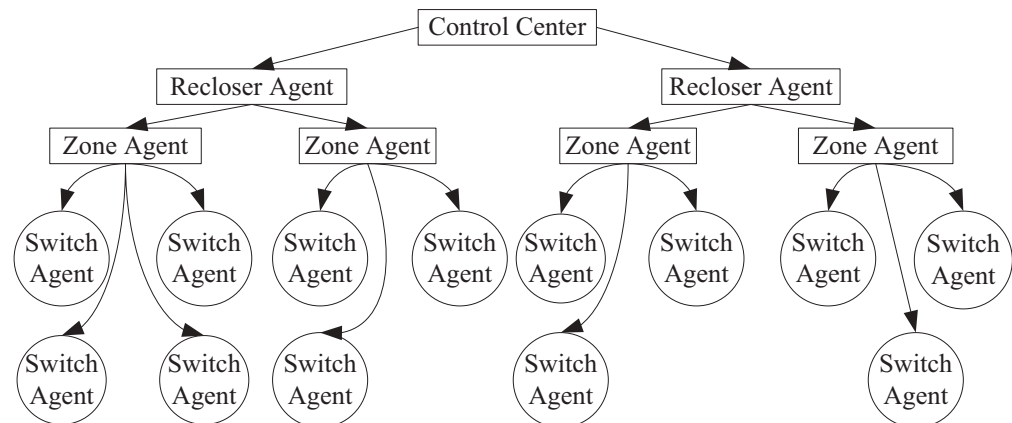
All of the reviewed literatures have been tested only in MV distribution network except (Xu et al., 2017). The qualitative comparison of the centralised techniques has been summarised in (Srivastava & Bhat, 2016). Their performance in the LV distribution network is still needed to realise their effectiveness in part of the network. Centralised control methods have a wide view and access to all network data and are able to find the global optimal solutions. Nevertheless, they tend to be insufficient since they are highly sensitive to system failures and should deal with large amount of data which need powerful processing capabilities.

4.2.2. Distributed approaches for service restoration

Distributed approaches have been introduced as the control method to get rid of the disadvantages of the centralised approaches. Multi agent systems (MAS) have emerged as a competitive technology for implementing distributed control in self-healing systems. Control decision of the network can use decentralised, distributed or hybrid architecture (Acharya & Nath, 2015; Jayasinghe, Thantrige, & Udayanga, 2015) depending on the level of automation of the distribution network. In the decentralised architecture, control decisions are done at the substation levels. Each agent at the substation shares its information with neighbouring substations' agents. In distributed architecture, agents with control decision are spread throughout the distribution network, control is based on locally processed data. Hybrid architecture combines the advantageous of both decentralised and distributed architectures for enhanced decision making. Figure 5 shows a hybrid/hierarchical architecture (Ghorban et al., 2013) commonly used in multi-agent systems.

Significant number of studies have been conducted in the MAS-based service restoration with different objectives and using different techniques for solving service restoration optimisation problem so as to ensure that power is restored as soon as possible while satisfying operational and topological constraints. Techniques used to solve the service restoration optimisation problem in distributed control paradigm are GA (Ghorban et al., 2016), PSO, Fuzzy logic (Elmitwally, Elsaid, Elgamal, & Chen, 2015), Expert systems (Nagata & Sasaki, 2002), MILP (Hossein Sekhavatmanesh & Cherkaoui, 2018) and heuristic (Solanki et al., 2007) approaches. Different issues are considered in the MAS-based restoration plans including load shedding, load prioritisation, load variability, DGs, load curtailment and others for improved efficiency, reliability and adaptability (Zidan et al., 2017). Few studies have gone further by incorporating the learning strategies in the MAS-based service restoration as explained in Section 3.3.3.

Figure 5. Hierarchical Multi-Agent System Architecture.



4.2.3. RL in MAS-based fault location and service restoration

A hybrid MAS framework with a Q-learning algorithm to support fast restoration of power systems following catastrophic disturbances was presented in (Ye, Zhang, & Sutanto, 2011). The agents used Q-learning algorithm in combination with restoration optimisation algorithm to take advantages of restoration experience, making more accurate decision in less time. The framework used central agent suggestions for their decision-making and tested only for general power grid systems. Modification of the Q-learning algorithm to be used in distribution systems was studied by (Ghorban, Choudhry, & Feliachi, 2014a). In (Ghorban et al., 2016), a hierarchical coordination strategy for fault location, isolation, and restoration in PDS with learning capabilities was presented. It has also been revealed that, MAS with learning capabilities has the influence of reaching at global optimal solution in distributed control methods.

To the best of the authors' knowledge, only few studies have been done which incorporate learning in the power systems service restoration. In these studies, stochastic nature of load demand and DGs was not considered. More research is needed to incorporate the stochastic nature of load demand and DGs in the MAS- based learning service restoration for improved efficiency.

5. Discussion on MAS-based approaches for the FLSR

Multi agent-based strategy is completely scalable and results to the optimal solution with desirable higher accuracy computed within short period of time and using low processing capability (Hossein Sekhavatmanesh & Cherkaoui, 2018). Multi agent system become more efficient during FLSR depending on the designed architecture, optimisation algorithm used and consideration of other factors like load priority, load shedding and uncertain nature of load profile and DGs. Table 1 summarises distributed approaches for FLSR by comparing their basic attributes like optimisation technique used, aspects considered, MAS architecture, strength, limitation and load/DG prediction method used. The progress of FLSR techniques can be clearly observed in the table. The abbreviations used in Table 1 are explained in Table 2.

Out of 21 MAS-based studies summarised in Table 1, it has been observed that the commonly used optimisation methods are the heuristic algorithms, metaheuristic methods, rule-based methods and expert systems, this is due to their simplicity of implementation and less computationally intensive. However, these methods can suffer from local optimality problem. Different aspects including load shedding, DGs, load priority, load variability and uncertainty induced DGs during restoration problem, for improved robustness of the MAS- based approach have been considered. It has been observe that only five studies (Ghorban, Choudhry, & Feliachi, 2014b; Hossein Sekhavatmanesh & Cherkaoui, 2018; Sharma et al., 2016, 2018; Zidan & El-Saadany, 2012) have considered the uncertainty induced by both load demand and DG and within these studies, two

Table 1. Summary of the MAS-based Fault Localisation and Service Restoration Method

Paper	Optimisation method	Architecture	Strength	Limitation	Aspects considered					Prediction method
					C1	C2	C3	C4	C5	
(Solanki et al., 2007)	Heuristic	Fully decentralised	Incorporation fully decentralised restoration, load priority and load shedding	Agents have limited view of system states. System may not be able to find the solution due to use of heuristic	✓	✓	✓	x	x	LOAD/DG
(Li, Sun, Wen, Cheng, & He, 2012)	Rule based	Full decentralised architecture	Proposed MA can handle cascading failure	Only one agent was used for decision making (high intelligence) (Control load, DG, switches)	✓	✓	✓	x	x	
(Sharma, Srinivasan, & Trivedi, 2015)	Heuristic	Decentralised	A novel idea for using Vehicle to grid feature for service restoration. EVs do not have stochastic nature.	System may not be able to find the solution due to use of heuristic. Used only despatchable DGs and constant load.	x	✓	✓	x	x	
(Ghorban et al., 2014b)	Non-Linear programming	Hierarchical architecture	Agents have load prediction capability	Requires centralised agent for decision making. Fuzzy-based prediction is network dependent	✓	✓	✓	✓	✓	A2/B2
(Ghorban et al., 2014a)	Integer non-linear optimisation	Hybrid	Used Q- learning with restoration optimisation algorithm to take advantages of restoration experience	Use of Q matrix for knowledge storage can lead to curse of dimensionality as the network expands.	x	x	✓	x	x	
(Ghorban et al., 2016)	GA	Hierarchical coordination strategy	Distributed approach for FLRS while using higher level agents with learning capabilities for service restorations	Multi-fault scenarios were not done, Reliance on feeder agent for service restoration, Use of Q matrix for knowledge storage can lead to curse of dimensionality as the network expands.	x	✓	✓	x	x	

(Continued)

Table 1. (Continued)

Paper	Optimisation method	Architecture	Strength	Limitation	Aspects considered					Prediction method
					C1	C2	C3	C4	C5	
(Elmitwally et al., 2015)	Fuzzy rules	Hybrid	Developed method for voltage adjustment after supply restoration	Fuzzy rules are system dependent.	✓	✓	✓	x	x	LOAD/DG
(Tsai & Pan, 2011)	BDI approach (Decision Tree)	Full distributed	Applied MAS to solve SR in distribution systems using full distributed architecture	Only constant current loads were considered	x	x	x	x	x	
(Nagata & Sasaki, 2002)	Expert system	Layered Architecture	Proposed MAS for restoration using one centralised agent for decision making Less communication due to use of local information	Requires centralised agent, large no of agents, System may not be able to find the solution due to use of heuristic	✓	x	x	x	x	
(Zidan & El-Saadany, 2012)	Expert system	Cooperative MAS architecture	Designed MAS can locate, isolate and restore the out-of-service loads. Minimised the impact of load variation to restoration	Rule based is network dependent. Island operation of DGs was not considered.	✓	✓	✓	✓	✓	A5/B5
(Avila et al., 2015)	Not Stated	Decentralised	Proposed capacity-based SR using MAS Incorporated prediction methodology in SR algorithm	During restoration only despatchable DGs were considered.	✓	✓	✓	✓	✓	A4/x
(Chouhan, Mohammadi, Feliachi, Solanki, & Choudhry, 2016a)	Graph theoretic	Hybrid	Proposed MAS has fault detection capability	Requires a centralised agent for decision making	x	✓	x	x	x	

(Continued)

Table 1. (Continued)

Paper	Optimisation method	Architecture	Strength	Limitation	Aspects considered					Prediction method
					C1	C2	C3	C4	C5	
(Sharma et al., 2016)	Heuristic rules and maximum likelihood estimation decision	Decentralised	Considered the stochastic nature of RDGs and Load demand	Obtain suitable solution instead of optimal one Prediction based on ARIMA is not effective in expressing non-linear relation	✓	✓	✓	✓	✓	A1/B1 LOAD/DG
(Abel Hafez, Omran, & Higazi, 2018)	Expert systems	Decentralised	The agents are distributed in zones along the feeder, the decision-making agent depends on the fault location	Load and DGs variability nature not considered	✓	✓	✓	x	x	
(Habib et al., 2017)	Not stated	Decentralised	Proposed MAS for FLSR. Used only current for fault location and isolation	Dependency on one agent for decision making	x	✓	x	x	x	
(Abilkhassenov, Auketayeva, Berikkazin, Jarmwal, & Nunna, 2018)	GA	Hybrid	Proposed hybrid MAS for SR in Distribution systems with DGs and Electric Vehicle integration	Load and DGs variability nature not considered. Only voltage and current constraint were considered.	x	✓	✓	x	x	
(Sharma et al., 2018)	Heuristic rules	Decentralised	Considered the effect of uncertain fault duration	System may not be able to find the solution due to use of heuristic rules.	✓	✓	✓	✓	✓	A3/B3
(Hossein Sekhavatmanesh & Cherkaoui, 2018)	Second-order cone programming	Hierarchical and decentralised	Agent interaction is designed to build reduced model of the network part to participate in restoration.	Performance on only single fault was tested.	✓	✓	✓	✓	✓	A3/B3
(Ghorban et al., 2013)	Not applicable	Distributed	Both MAS and power system developed in MATLAB and hence no interfacing required	Service restoration was not considered.		✓				

(Continued)

Table 1. (Continued)										
Paper	Optimisation method	Architecture	Strength	Limitation	Aspects considered					Prediction method
					C1	C2	C3	C4	C5	
(Thejas et al., 2014)	Not applicable	Distributed	Both MAS and power system developed in MATLAB and hence no interfacing required	Service restoration was not considered.		√				LOAD/DG
(Lin et al., 2018)	Not applicable	Distributed	Thorough analysis on the fault isolation has been done in which the developed MAS can isolate within 0.05s	Service restoration was not considered.		√				

Table 2. Description of Abbreviations Used in Table 1

Aspects considered	Load prediction methods	DGs prediction methods
C1: Load shedding C2: Distributed Generation C3: Load Priority C4: Load Variation C5: Uncertainty in DGs	A1: Statistical models A2: Fuzzy-based A3: Neural Networks A4: Ensemble Learning A5: Not stated	B1: Statistical models B2: Fuzzy-based B3: Neural Networks B4: Ensemble Learning B5: Not stated

(Hossein Sekhvatmanesh & Cherkaoui, 2018; Sharma et al., 2018) have used neural network, one (Sharma et al., 2016) used statistical models and one (Ghorban et al., 2014b) used fuzzy approach for forecasting load demand and DGs. One study (Zidan & El-Saadany, 2012) did not specify the forecasting technique used for considering variability in load and DGs. A study done by (Avila, Soo, Yu, & Chu, 2015), considered the uncertainty induced by load demand only. Moreover, only two studies (Ghorban et al., 2014a, 2016) have used the RL in MAS so as to take advantage of the knowledge base during supply restoration. Finally, within 21 studies, three studies (Ghorban et al., 2013; Lin et al., 2018; Thejas, Rao, & Kavitha, 2014) focused only in fault location and isolation, 16 studies focused only in service restoration and two studies (Ghorban et al., 2016; Habib et al., 2017), considered FLSR as a complete problem.

Studies which have considered the uncertainty nature of load demand and/or DGs have revealed that consideration of uncertainty guarantee few switching operations, achieve high power quality, supply the maximum number of customers and helped in avoiding islanding operation (Hossein Sekhvatmanesh & Cherkaoui, 2018; Sharma et al., 2016; Zidan & El-Saadany, 2012). Scenarios for comparison with the use of the pre-fault and peak values for the load demand and renewable DG capacity have been analysed in these studies. Authors discovered that, the use of peak values results to high power quality but may result to limited load restored and large number of switching operations while the use of pre-fault data result to overloading or underloading after restoration process.

6. Challenges and future directions

Renewable energy sources including solar panels and wind turbines integration in distribution power systems is of higher importance for increased capacity, reliability and overall power quality. The downside of renewable sources is its intermittency nature. Stochastic nature of load demand and renewable DGs have significant effect in the service restoration problem optimisation as they can lead to underutilisation of available capacity or underestimation of the peak load leading to overloading PDS. Little attention has been paid to the integration of forecasting methods with distributed algorithms for power restoration. High accuracy in forecasted load and DG capacity is needed. Most of the existing reports in the multi-agent-based service restoration studies (Ghorbani, Chouhan, Choudhry, & Feliachi, 2013) use the constant peak hour load during service restoration. Furthermore, studies (M. J. Ghorban et al., 2014b; Sharma et al., 2016) in service restoration which consider load variation used rule-based and classical statistical model approaches respectively in modelling the stochastic nature of load demand and DGs which are inefficient in nonlinear and non-stationary systems (Ouyang et al., 2017). Statistical methods also suffer from complexity of modelling, lack of flexibility and low accuracy (Marin, Garcia-Lagos, Joya, & Sandoval, 2002). Moreover, these methods have the disadvantage of being poorly generalisable for system specifications and lack the potential to incorporate accurate predictions for the occupant behaviour (Ouyang et al., 2017). It is argued that data-driven methodologies such as neural network and deep learned network are therefore more suitable in short term load and DG forecasting as can effectively work in variables with non-linearity relationship. There is a need of using advanced data driven in the short-term forecasting of load demand to improve efficiency. A study done in (Hossein Sekhvatmanesh & Cherkaoui, 2018) employed artificial neural networks for demand and capacity forecasting in MAS-based approach. However, the study was tested for single fault only. More studies are still needed in the use of deep learning in MAS-based service restoration approaches.

RL has also shown excellent performance in optimising agents' utilities under dynamic environments in MAS-based power systems management (Foruzan et al., 2018; Leo, Milton, & Kaviya, 2014; W. Liu, Wen, Shen, & Zhang, 2017) and other applications like traffic control (Y. Liu, Liu, & Chen, 2017) and robotic control (Arulkumaran, Deisenroth, Brundage, & Bharath, 2017). Indeed, some studies (Ghorban et al., 2014a, 2016; Ye et al., 2011) used RL to improve agents' decision making and increase their utility in service restoration. However, authors did not consider the stochastic nature of load and assumed that the restoration is only done by main grid without considering the presence of DGs, while it is more realistic to consider all agents' variability in models that aim to maintain load-generation balance and reducing unnecessary load shedding. The knowledge base was stored in the Q-table which becomes inefficient as the number of states increases which can be caused by the dynamic nature of the load and DGs for modern distribution networks. The electrical distribution network is large, dynamic and influenced by unpredicted events due to stochastic nature of load demand and DGs (Foruzan et al., 2018). Therefore, the MAS-based service restoration adapting the RL approach for PDS with DGs incorporating the stochastic nature of load demand and DGs is needed. Furthermore, deep learning (Jiang & Yang, 2016) algorithms have achieved record-breaking performance in several applications. Researchers make use of the deep learning in reinforcement-based multi-agent systems to further improve the decision making in agents (Kashihara, 2017; Yang, Merrick, Jin, & Abbass, 2018). Deep RL works well in dynamic environments. However, deep RL has not been used in the existing studies for FLSR to the best of the researcher's knowledge. Therefore, integration of deep learning in the distributed service restoration approaches for improved decision making need to be further researched.

DSM through load curtailment have also been found to improve the service restoration optimisation problem for increased capacity in case of insufficient supply (Alowaiifeer, Almuahini, & Alsaggaf, 2015; Kleinberg et al., 2009, 2011). Centralised approaches have been employed in these studies. MAS- based approach for service restoration taking into account load curtailment need to be investigated.

7. Conclusion

In this paper, fault location and service restoration techniques for distribution grids namely centralised and distributed approaches have been reviewed and scrutinised. Emphasis has been done on the distributed control approaches in which a qualitative analysis has been done by discussing different aspects considered in the restoration plan and load demand and renewable generation prediction methods. Architectures and optimisation methods used during service restoration have also been discussed. It is clear from the discussion that both load and renewable energy resources have stochastic nature and have significant impact to the service restoration as helps in reducing overloading or underloading after restoration and increasing the number of restored customers as compared to the use pre-fault data or peak values respectively. However, most of the existing MAS-based studies for FLSR has not considered the impact of the load variability and uncertainty in renewables DG with only few using statistical methods, fuzzy logic and neural network in developing forecasting model. Consequently, more researches should be conducted to explore the improvement of available distributed service restoration techniques to accommodate the stochastic nature of load and renewable energy resources making use of advanced data driven approaches. Apart from the consideration of the stochastic nature, the use of the RL in the multiagent systems is of great importance for fastening the process through using the previous knowledge in control decision.

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Author details

Rukia J. Mwifunyi¹
E-mail: rukiahilda@gmail.com
Mussa M. Kissaka²
E-mail: mmkissaka@gmail.com
Nerey H. Mvungi¹
E-mail: nhmvungi@gmail.com

¹ Department of Computer Science and Engineering, University of Dar es Salaam, Dar es Salaam, Tanzania.

² Department of Electronics and Telecommunications Engineering, University of Dar es Salaam, Dar es Salaam, Tanzania.

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