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Distribution of renewable energy through the energy internet: A routing algorithm for energy routers

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Abstract

Fossil fuels are rapidly running out, and with the demand for environmentally friendly energy sources increasing, power grids are looking for distributed power generation-based renewable resources. The distribution of these energy sources is significantly linked to the development of smart microgrids, which are also extensively connected with the energy internet. This paper explores the energy internet operation, focusing on developing a routing algorithm for an energy router. The energy routing algorithm is further substantiated with the aid of simulations. This algorithm can find all the paths available for energy transmission between two nodes and selects the track with the most negligible losses as the path for transmission. All the possible routes are displayed along with the losses associated with each direction to ensure that the approach with the lowest losses is taken. The algorithm is also tested for 24 h at an hourly interval to observe the change in power transmitted on the system.

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Keywords: Distributed power generation; Internet of energy; Internet of things; Renewable energy; Smart grid

1. Introduction

The depletion of fossil fuels and the environmental pollution of traditional energy sources have led to the demand for clean energy. Furthermore, there is a global increase in the need for electricity as more and more development are many types of renewable energy sources (RES), such as wind, occurs. This has consequently increased electricity tariffs [1–3]. There hydroelectricity, and solar energy, that can be harnessed to meet the ever-growing energy demands of the consumer. Solar thermal energy deals with heating, mainly for household purposes, by heating water using the sun's direct energy. Solar electricity uses the photovoltaic (PV) process to convert the

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radiation emitted from the sun into electricity. The output electricity depends on the array voltage, temperature, and insulation [4]. RESs have several advantages that can help address the energy demands; however, limitations such as power fluctuations may cause damage to equipment. The oscillations also negatively affect the system's stability [5,6].

In 1978, distributed generation (DG) was proposed, consisting of a microgrid (MG), an energy storage device, and a load. However, DG does have its limitations in coping with energy demands. For example, structural changes are needed in the currently available infrastructure [7–9]. The MG is a distribution system allowing energy management support for grid-tied and island systems [8]. The future of DGs will require innovative, intelligent grid systems. This means that MGs will be needed to operate efficiently and intelligently in the island, grid-tied mode, or both. The MGs, however, require the standards of operation to be developed. The limitations of the smart grid can be reduced with the development and integration of the energy internet (EI). The EI is an integrated system of DG, RESs, real-time monitoring, information sharing, and viewing of energy tariffs [2,10]. The EI addresses environmental issues by replacing traditional energy resources with clean energy [11]. The Future Renewable Electric Energy Delivery and Management (FREEDM) system introduces a model for energy delivery by applying distributed energy with renewable resources [12]. This system can be observed as one that works similar to any consumer's interaction with the internet by using the concept of Plug-and-Play [13,14]. It should be noted that real-time data coordination on energy usage implies that energy consumption and efficiency can be improved.

The core of the EI is the energy router (ER) that is used for the operation and management of the EI. In addition, it is responsible for power-forwarding and exchanging information between the energy pairs. The energy router is also responsible for optimally routing the energy between energy pairs while reducing the transmission loss between the pairs [14,15].

The objectives of this paper can be summarized through the following points:

- Formulate a study of the energy internet and the energy router.
- Explore the different algorithms used in energy routers for energy routing.
- Develop a potentially new routing strategy that can be applied for energy routing throughout theoretical analysis and simulations to validate the performance of the system.
- Discuss and analyze the proposed algorithm.

An adaptation of the Dijkstra algorithm will be proposed as a routing algorithm. The algorithm will find the most energy-efficient path to transmit the energy between the source and the destination. This considers all the losses within the energy router as well as the transmission losses on the route taken for energy transmission.

2. Energy routing algorithms

2.1. Minimum loss routing algorithm

The minimum loss routing algorithm (MLR) is based on real-time transactions, while the congestion of end-to-end power transmission is alleviated. The energy router in the MLR algorithm comprises a physical and an information layer. The physical layer is the converter that acts as a plug-and-play device for the various RESs, loads, and storage devices. The information layer controls the flow of energy, which will help realize an optimal transmission path for the energy. In addition, the information layer ensures that all the power transmission requirements are met. This includes implementing the routing procedures and commencing/dismissing power transmission [16].

2.2. A semi-decentralized routing algorithm for minimum-loss transmission in community energy internet

This algorithm proposes that a community-scaled power network is realized, where energy storage, RESs, and loads are interconnected through the energy internet. It uses a converter containing multiple inputs, output ports, and routing control modules. Power is exchanged through a direct current (DC) bus that is interconnected via power converters to distributed generation, energy storage modules, and the loads to be supplied. Individual ERs perform the route calculations. When no paths are overlapped, the ER will take a decentralized approach for energy transmission as globally optimal solutions will be sufficient for energy transmission. A decentralized system is used when the ER detects that overlapping has occurred. The ER uses a depth-first search (DFS) algorithm to determine all the routes connecting the energy trading pairs. Once the optimal path has been found, the energy dispatch can be formulated using non-linear programming [15]. The ER is designed to share information such as transmission line characteristics, routing information, and more through sharing platforms.

2.3. Dijkstra algorithm

The Dijkstra algorithm is a well-known algorithm used to find the shortest path between two points [17] and can be used to solve energy routing problems between multiple trading pairs. The two pairs, from their perspective, determine the optimal power transmission route. The track can be of the shortest distance or the lowest cost between two nodes [18]. Compared to the Bellman–Ford algorithm, the running time of the Dijkstra algorithm is insufficient if implemented correctly. This paper implements this algorithm to find the shortest path between the two energy routers.

2.4. Methodology and implementation

As discussed in the previous section, the energy internet links different forms of energy, renewable and non-renewable. In this study, the electric network of the system consists of the utility grid, battery storage systems, and solar power as the renewable energy source. Also, only the transmission line and the energy router form part of the electric network in this paper. The power within the transmission line for 24 h is sampled hourly to see how the power availability changes affect the transmission path chosen. The parameters used in this study were obtained from [15].

The proposed algorithm is an adaptation of the Dijkstra routing algorithm [17]. The system consists of several energy routers with various efficiencies, transmission line resistances, and different paths connecting the energy routers. First, the source and destination router are selected, and the different paths between the two routers are identified using the algorithm. Once all the tracks have been computed, the losses resulting from the transmission line and energy router internal losses are calculated. The algorithm then selects the path for energy transmission's most negligible losses.

Fig. 1 shows the modeling strategy and schematic used to explain the concept. Table 1 features the parameters of the system.

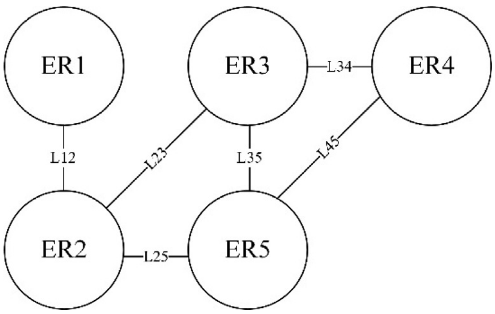


Fig. 1. Energy routing path: Basic system.

3. Theoretical analysis and simulations

Routing algorithms used by the EI are typically linked to the graph theory. This is represented by a set of nodes and edges.

$$G = (N, E, W) \tag{1}$$

where N represents the set of nodes or the junctions on a routing map, E is the edges, where the edges are the path between two nodes, and W is the weight of the edges or the distance between two nodes. When no edges are available between two nodes, the weight, W, is set to zero [19].

Table 1. Energy router and transmission line parameters: Basic system.

ER no.	Capacity (kW)	Efficiency (%)	Line	Capacity (kW)	Voltage (V)	Resistance (Ω)
1	20	97%	L_{12}	45	400	0.21
2	22	100%	L_{23}	40	400	0.6
3	15	97%	L_{25}	30	400	0.55
4	18	97%	L_{35}	24	400	0.6
5	20	100%	L_{34}	30	400	0.94
–	–	–	L_{45}	32	400	0.46

The minimum path from the source to the sink was determined using distances with the Dijkstra algorithm. However, the shortest distance is not necessarily the optimal path for energy transmission. Therefore, the algorithm calculates the best path based on the transmission line and ER losses. In addition, parameters such as the power transmitted need to be defined.

The route of the most negligible losses is used to transmit energy. This is calculated by the loss factor depicted in Eq. (2).

$$L_s = \sum_{k_s=1}^{N_s} (\sum W_i + \sum W_{ij}) \tag{2}$$

where W_i is the power losses within the energy router, W_{ij} is the conduction losses of the transmission line. Eq. (3) calculates the converter loss.

$$\sum W_i = P_{k_s} * (1 - \eta_i) \tag{3}$$

With η_i is the efficiency of the energy router i and $P_{ks\_}$ is the power required by the destination energy router from the source, i.e. the power to be dispatched on the kth path. Then, Eq. (4) calculates the losses within the transmission line during transmission.

$$\sum W_{ij} = \frac{R_{ij}}{V_{ij}^2} * \left[\left(P_{k_s} + P_{-k_s} + P_{ex(ij)} \right)^2 - P_{ex(ij)}^2 \right] * \frac{P_{k_s}}{P_{-k_s} + P_{k_s}} \tag{4}$$

With R_{ij} is the resistance of the transmission line connecting the ERs and V_{ij} is the voltage, P_{-k_s} is the total power transmitted through the remaining paths shared on transmission lines i and j, and $P_{ex(ij)}$ is the existing power on the transmission line before P_{k_s} and P_{-k_s} is added. For simulation purposes, all the power components were set to 1000 W for the simple routing system and varied hourly for the complex routing system. The most efficient path between two routers using the Dijkstra algorithm were determined using the equations. Finally, two scenarios were used to compare the theory and the simulation, choosing the path between two routers close to each other and determining the path between two routers far apart.

3.1. The functionality of the algorithm: Basic system

3.1.1. Router 1 to router 2

$$L_s = \sum_{k_s=1}^{N_s} (\sum W_i + \sum W_{ij}) = 30 + 5.25 = 35.25 \tag{5}$$

Router 1 to Router 5

From router 1 to router 5, three possible paths can be followed:

- Path 1: $ER1 \to ER2 \to ER3 \to ER5$
- Path 2: $ER1 \to ER2 \to ER3 \to ER4 \to ER5$
- Path 3: $ER1 \to ER2 \to ER5$

Table 2. Results: Router 1 to 5.

Path no.	ER loss	Transmission line loss	L_s
1	60	43.75	103.75
2	90	55.25	145.25
3	30	19	49

The loss factor of each of the paths is calculated and summarized in Table 2. The three paths were determined as the possible paths between routers 1 and 5. The simulation results selected path 3: $ER1 \rightarrow ER2 \rightarrow ER5$, as the path for transmission with the most negligible losses.

3.2. The functionality of the algorithm: Complex system

The system in the previous subsection is simplified to illustrate the algorithm's functionality. However, as assumed in the previous method, the existing transmission line power and shared transmission paths do not stay constant at 1000 W in a real-world scenario. Therefore, the complex system tests the algorithm with the routing system described in [15]. The routing path is shown in Fig. 2.

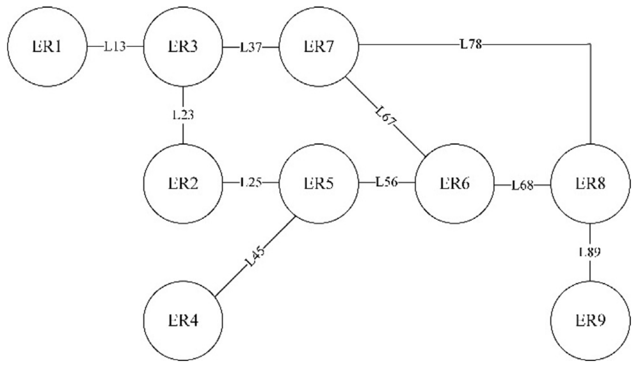


Fig. 2. Functionality of the algorithm: Complex system.

Table 3. Energy router and transmission line parameters: Complex system [15].

ER no.	Capacity (kW)	Efficiency (%)	Line	Capacity (kW)	Voltage (V)	Resistance (Ω)
1	20	98%	L_{13}	30	400	0.6
2	15	100%	L_{23}	20	400	0.64
3	10	98%	L_{25}	20	400	0.51
4	15	98%	L_{37}	45	400	0.94
5	15	100%	L_{45}	24	400	0.19
6	18	100%	L_{56}	20	400	0.45
7	20	100%	L_{67}	40	400	0.24
8	18	98%	L_{68}	30	400	0.21
9	20	98%	L_{78}	30	400	0.21
–	–	–	L_{89}	32	400	0.6

Table 3 illustrates the parameters of the energy router and transmission line. The path is used from ER 2 to ER 9.

Theoretically, there are three possible paths linking the two energy routers. The paths are the following:

- Path 1: $ER2 \rightarrow ER3 \rightarrow ER7 \rightarrow ER8 \rightarrow ER9$
- Path 2: $ER2 \rightarrow ER5 \rightarrow ER6 \rightarrow ER7 \rightarrow ER8 \rightarrow ER9$
- Path 3: $ER2 \rightarrow ER5 \rightarrow ER6 \rightarrow ER8 \rightarrow ER9$

Table 4. Power characteristics at different time intervals.

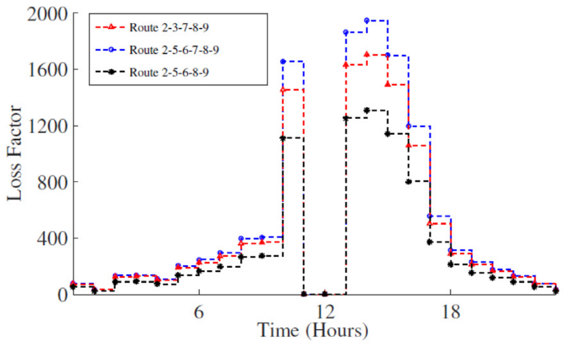
Hour	P_{k_s}	P_{-k_s}	$P_{ex\,(i,j)}$	Hour	P_{k_s}	P_{-k_s}	$P_{ex\,(i,j)}$	Hour	P_{k_s}	P_{-k_s}	$P_{ex\,(i,j)}$
00:00	1000	0	0	08:00	3200	350	170	16:00	6500	415	310
01:00	500	40	0	09:00	3200	375	250	17:00	4000	280	275
02:00	1500	75	100	10:00	4000	380	275	18:00	2700	230	255
03:00	1500	125	115	11:00	10 200	2525	2525	19:00	2200	110	210
04:00	1250	150	140	12:00	10 350	2400	3560	20:00	1800	80	195
05:00	2000	175	180	13:00	8500	415	390	21:00	1500	40	90
06:00	2300	250	150	14:00	8700	425	420	22:00	1000	20	45
07:00	2600	280	190	00:00	8000	450	410	23:00	500	0	0

The parameters in Table 4 were added to the algorithm to see how it comprehends power variation. The parameters are all measured in Watts. Finally, the constraint in Eq. (6) is applied to the system to ensure it does not operate beyond the capabilities of the system components.

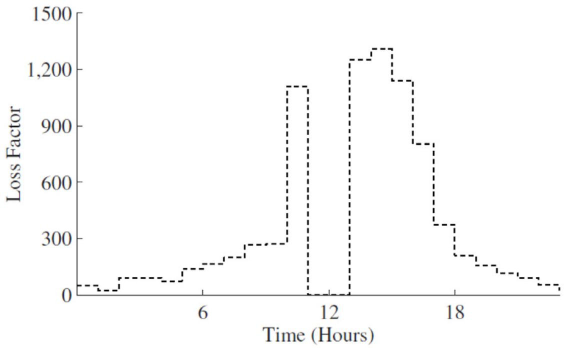
$$P_{k_s} + P_{-k_s} + P_{ex(i,j)} \leq min(P_{i-,j-cap}, P_{i-cap}, P_{j-cap}) \quad (6)$$

4. Discussion

The results obtained from the theoretical and simulations are compared and analyzed. The simulation algorithm adapts the Dijkstra algorithm to calculate all possible routes. The code for the algorithm calculates the shortest path first, appends the path in a list, and then calculates the next possible route if any. It loops through this until all the possible routes have been explored. When all the possible routes have been computed, the algorithm uses the energy router and transmission line parameters to calculate each route's total loss. Once this loss has been calculated, the path of the slightest losses, not necessarily the shortest in the distance, is set as the route for energy transmission. Two simulation results were obtained, the first of a simple routing system, as illustrated in Fig. 1, and a more complex one based on the study in [15], which is explained in Fig. 2. The simulations were performed using the programming language, Python.



(a) Loss Factor of each path of transmission.



(b) Plot of the loss factor on the most energy efficient pat (2-5-6-8-9).

Fig. 3. Theoretical and simulated illustration of the loss factor at different time intervals.

Theoretically, it was determined, with the aid of a spreadsheet, that the route with the minimum loss was path number 3, i.e. $ER2 \rightarrow ER5 \rightarrow ER6 \rightarrow ER8 \rightarrow ER9$.

Fig. 3 was plotted using the results from the simulation, showing the loss factor of each possible routing path.

4.1. General discussion

The energy routing algorithm works well with the given energy routing parameters. The algorithm can successfully calculate the most efficient paths, but this is only limited to single-path routing. The algorithm can be modified for multi-path routing, requiring high computational power. This, however, might be unrealistic due to the computational limitations of hardware available in the market. Therefore, the algorithm can be combined with a second algorithm for multi-path routing to overcome this. The system will then choose the algorithm to be used based on the complexity of the power to be transmitted.

4.2. Discussion of the basic energy routing path

The routing system in Fig. 1 was used for the calculations for the simple routing system. Two scenarios were used; scenario one considered the routers placed right next to each other, while scenario two considered the routers to be set far apart. The shortest route selected was from ER 1 and ER 2. According to the theory, only one possible path can be followed from energy router 1 to 2.

- $ER1 \rightarrow ER2$

The loss factor for transmission of energy was calculated to be 35.25. The simulated value was observed to be 35.25 as well. The longest path was set on the algorithm, and the results were observed to be similar between the theoretical and the simulated results. This was between router 1 and router 5. Three paths were determined theoretically as the possible route connecting the source and sink nodes. It is observed from the simulations that this is indeed true.

- Path 1: $ER1 \rightarrow ER2 \rightarrow ER3 \rightarrow ER5$
- Path 2: $ER1 \rightarrow ER2 \rightarrow ER3 \rightarrow ER4 \rightarrow ER5$
- Path 3: $ER1 \rightarrow ER2 \rightarrow ER5$

The simulations determined that the best path for energy transmission would be the third path, $ER1 \rightarrow ER2 \rightarrow ER5$, which was the same as the theoretical calculations. This further motivates the accuracy of the simulations. The loss factor was measured to be 49. The most significant loss factor of 145.25 was observed in the second routing path, $ER1 \rightarrow ER2 \rightarrow ER3 \rightarrow ER4 \rightarrow ER5$, and this can be accounted for the fact that there are more energy routers involved, thus increasing the number of losses through energy router conversions. This is summarized in Table 2.

4.3. Discussion of the complex energy routing path

The algorithm was tested using a more complex routing system. First, the algorithm was tested with different values of power that needed to be transmitted in a 24-h cycle. Then, the constraint in Eq. (6) was applied to the algorithm. If the sum of power within the transmission line exceeds the power capacity values of the routers and transmission lines in operation, the system would not transmit energy through that path but, instead, find an alternate route. The chosen path for the complex routing was from energy router 2 to energy router 9. Three possible paths were determined theoretically, namely:

- Path 1: $ER2 \rightarrow ER3 \rightarrow ER7 \rightarrow ER8 \rightarrow ER9$
- Path 2: $ER2 \rightarrow ER5 \rightarrow ER6 \rightarrow ER7 \rightarrow ER8 \rightarrow ER9$
- Path 3: $ER2 \rightarrow ER5 \rightarrow ER6 \rightarrow ER8 \rightarrow ER9$

Throughout the time interval, it was determined that the path for transmission would be Path 3, as this is the path with the most negligible router and transmission line losses. At hours 11 and 12, it was observed that no power was transmitted. This is because the power characteristic within the transmission line exceeded the capacity of energy router 2 of 15 000 W. This was the effect of adding the constraint in Eq. (6) to the algorithm. Thus, the algorithm would technically select another path for transmission; however, this is impossible considering that router 2 is the source. As a result, no energy was transmitted to protect the components involved. This is also observed in the graphs illustrated in Figs. 3a and b. The profile of the graphs suggests that as the power transmitted in the system increases, so do the loss factors, but when the power exceeds the capacities, the transmission stops completely. Comparing the simulated and the calculated values bear close resemblance, suggesting that the algorithm did calculate the loss factors correctly, considering all the changes in parameters per time interval. The highest loss factor measured was 1114.77 from the simulations, as shown in Fig. 3b, at hour 10, before transmission stopped — any variances resulting from the number of decimal places used between the two.

5. Conclusion

The energy internet is a new concept that will change the distribution of renewable energy. The research concluded that the core of the energy internet is the energy router, which is responsible for information sharing and energy routing. The energy internet does have its limitations in terms of infrastructure, computational constraints, and potential cyber security threats. This, however, will be improved as more research is done on the concept. Algorithms have been developed for energy transmission; however, most need practical implementations to conclude their authenticity. An algorithm for single-path routing was formed, and the algorithm first finds all the possible paths between the source and destination nodes. When all the tracks have been explored, the losses are calculated, and the track with the most negligible losses is set as the default path for transmission. Due to linear limitations, the algorithm is limited because it can only be used for single-path routing.

In the future, the algorithm can be combined with a second algorithm to allow for multi-path routing. The new algorithm will always use the algorithm proposed in this paper as the path for transmission if it is just single-path routing. If multiple routers request energy for transmission, the second algorithm will be implemented to solve the multi-routing problem. The interface of the algorithm needs to be improved to allow it to get data from existing routers about their efficiencies and the transmission line properties. An energy-sharing platform needs to be designed to store the relevant information on the energy routers' efficiency and the transmission line parameters that are used in the algorithm for calculations. The platform uses plug-and-play technology to ensure that all the parameters of the energy router and the transmission line are synced into the system automatically.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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