Creating Active and Reactive Power Reserve Zones for Large-Scale Electric Grids

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***Abstract*—This paper proposes a strategy to partition large electrical grids into active power and reactive power reserve zones by applying a clustering algorithm to the Laplacian of the power system Jacobian matrix. This strategy is applied to two large synthetic cases with around 7k and 24k buses, and the results are provided. This partitioning further facilitates determining each zone's required real power and reactive power reserve types.**

***Index Terms*—required reserve, active power reserve, reactive power reserve, synthetic grids, reliability, resiliency**

I. Introduction

In large-scale electric grids, reserves are critical to maintaining system reliability. Power system reserves are defined as available generating capacity that is "reserved" for generator contingency events to allow for generator redispatch in the events such as a line outage, to account for load increase in the upcoming hours, or for real-time balancing of generation and load. These electrical reserves are of various types such as regulating up and down reserves, spinning, non-spinning, and reactive power reserves. Regulating up and down reserves are related to the ramping capability of generators to adjust the amount of real power being generated to meet the demands in cases of sudden changes. Spinning and non-spinning reserves are two types of real power reserves that are used to maintain the stability of power systems based on the online or offline capacities of generators. Reactive power reserves are also required to maintain the stability and reliability of the system, as changes in reactive power demand can lead to voltage fluctuations and instability. Reactive power reserves can be provided by a variety of sources, such as static VAR compensators, synchronous condensers, and shunt capacitors. [1]

Large-scale electric grids are commonly partitioned into various smaller regions (zones) for various purposes, including the control area and determining the required reserve in each zone. The North American electric grid is divided into four interconnects: Western Interconnection (WI), Electric Reliability Council of Texas (ERCOT), Eastern Interconnection (EI), and the Quebec Interconnection. Further zone formation is done based on utility ownership and transmission management. This division was limited by the evolution of the grid over time and predicated on factors such as politics, geography, human occupancy of land, and ease of market administration. For example, the EI is a large network that spans across several states in the eastern part of the United States and parts of eastern Canada. It includes several sub-areas that are managed by various regional transmission organizations (RTOs) and independent system operators (ISOs) including Midcontinent Independent System Operator (MISO), Southwest Power Pool (SPP), ISO New England, and New York ISO. Each of these areas develops Local Resource Zones (LRZ) based on geography to plan reserve adequacy to meet demand and contingency requirements reliably [2]. If the reserve zones are defined such that the reserve providers are geographically closer to the point they are required, the concerns of transmission line congestions are decreased. To do this, it is suggested to partition larger grids into several smaller zones based on the possible similarities in the reserve requirements and determine the required reserve for each zone.

Kirchhoff's laws determine the electrical behavior of the network, causing power to flow in ways that can be non-intuitive. Varying transmission line lengths create paths of varying impedances causing unequal power flows through them. Additionally, power systems follow the adage "vars don't travel," i.e., reactive power often does not travel large electrical distances and needs to be generated close to where it is consumed. Local availability of sufficient real and reactive power capacity resources is necessary to minimize losses in the grid and maintain reliability in case of emergency scenarios. Hence, a good partitioning algorithm should create zones such that intra-zonal components exhibit very high electrical connectivity with sufficient capacity reserves while minimizing unscheduled inter-zonal power flows.

An algorithm is proposed in [3] to partition the power grid for controlled islanding to avoid cascading outages. Similarly, [4] created an algorithm to define voltage control areas using Voltage Stability Security Assessment and Diagnostic (VSSAD) method. In [5], spectral clustering is applied to electrical connectivity to divide the network into zones such that electrically closer buses are within one zone. The authors in [6] use statistical clustering techniques to determine real power reserve zones by employing electrical distances and Power Transfer Distribution Factors (PTDF) differences. In [7], spectral clustering is applied to admittance-based or power flow-based Laplacian for partitioning a 900 bus system in

Great Britain. While these algorithms divide the power grid into either real power zones or voltage control areas, the algorithm proposed in this paper creates both real and reactive power zones.

The algorithm proposed in this paper utilizes eigenvalues and eigenvectors of the Graph Laplacian of the power system Jacobian to cluster the graph into a predefined number of zones. This algorithm is then applied on large synthetic grids with 7k and 24k buses to create real and reactive power zones. These zones can be used to determine the required reserve provided closer to the demand and increase the grids' reliability. This partitioning is used to determine each zone's required level of real and reactive power reserves. The proposed strategy is general and can be applied to any other electrical grid.

II. Methodology

A. Clustering Large Scale Electric Grids Into Active and Reactive Power Reserve Zones

The proposed approach clusters buses based on their connectivity parameters and designates them to the real and reactive power zones separately. These clusters of buses are used to define the zonal level required reserve capacity. Required real power reserve values are determined as a percentage of peak MW demand defined by the National Renewable Energy Laboratory (NREL) for various utilities. Most utilities define a voltage bandwidth within which the voltage profile is expected to remain despite contingency scenarios. For example, in ERCOT, the emergency operating limits for the voltage profile are within 0.9 pu to 1.1 pu [8]. The voltage operating limits combined with the Q-V curve of a bus are used to get the maximum and minimum reactive power injection required at that bus.

The work presented in [7] is used as the basis of the spectral clustering algorithm in this paper. It is modified to also include voltage and reactive power relationships to reveal the underlying connectivity, which is leveraged to determine the reactive power zones.

Mathematically, spectral clustering can be applied to network graphs to generate k-clusters by utilizing k-eigenvalues and the corresponding eigenvectors of the graph Laplacian. The power grid can be treated as a network graph with the buses as nodes, and the transmission lines as edges. For simplification, multiple transmission lines between buses are considered one edge, and all edges are undirected. Two separate graph Laplacian matrices are used for determining the real and reactive power clusters of buses, respectively. The value of k (the number of clusters) is predetermined for each grid based on the size of the grid. It should be noted that the real power and reactive power reserve zones are just used to determine the required reserve values of each zone for improving the reliability and resiliency of the grid. These areas are not control areas of a geographically partitioned grid, and since there is no coordination between the reserve zones, the number of reserve zones can be determined arbitrarily. Since reactive power has more local impact, it is beneficial if the number of reactive power reserve zones is more than real power reserve zones.

Also, power networks cannot be simply treated as graphs with equal weights on all edges. When creating the graph Laplacian, the inherent electrical properties of a power network should be translated as weights to quantify the connectivity of nodes and edges. A few characteristics of the real and reactive power flows should be considered before partitioning the grid into zones. To avoid transmission congestion due to limited power flow capacities within the real power zones, it is essential to have lines with high MVA capacity within a zone and lines with a lower MVA capacity between two zones. Hence, the MVA rating of the transmission lines is a good representation of the underlying real power flows, and it can be used as an edge weight for determining the weighted Laplacian for real power zones. This satisfies the requirement to minimize intrazonal congestion and reduce power transfer between zones.

The same reasoning cannot be applied to reactive power because it does not really "flow" through the lines the same way real power does. Alternatively, reactive power injection at a bus affects the voltage profile at that bus and displays a strong correlation. Hence, for creating the weighted Laplacian to determine reactive power zones, the correlation between changes in bus voltage and reactive power injections captured by the fourth quadrant of the Jacobian,

$$\begin{bmatrix} \frac{\partial P}{\partial \theta} & \cdots & \frac{\partial P}{\partial V} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q}{\partial \theta} & \cdots & \frac{\partial Q}{\partial V} \end{bmatrix}$$

is leveraged as node weights [9]. Buses with high dV/dQ sensitivity are clustered together into one reactive power zone.

While the properties of the power grid help determine the underlying connectivity, it is beneficial to include geographical distance into the Laplacian as an additional weight. The geographical coordinates of the buses are used to create a Laplacian matrix of the distance between every two buses. This is added to graph Laplacians calculated for real and reactive power zones as indicated in the Eq. 1,2 where Ł$_d$ refers to a geographical distance matrix and Ł$_l$ shows line capacity matrix. Ł$_{QVJac}$ shows the dQ/dV part of the Jacobian matrix.

$$L_{Pzones} = L_d + L_l \tag{1}$$

$$L_{Qzones} = L_d + L_{QVJac} \tag{2}$$

To find k-zones of a network, (k+1)-eigenvalues and their corresponding eigenvectors of the graph Laplacian matrix are calculated. The number of zero eigenvalues of a network graph Laplacian represents the number of connected components. Since a power system network is a single connected component, the first eigenvalue is zero. Then as the last step of spectral clustering, the k-means algorithm is applied to cluster the last k-eigenvectors. One drawback of selecting k-means as a choice of clustering algorithm is that the value of k needs to be predefined. The authors in [10] suggest a method to determine an optimal value of k. Currently, this is not incorporated into the algorithm used for creating zones. Another drawback of using k-means is that different sets of starting points may lead to different clusters. One simple solution that is currently used is to try different starting points and use larger K values [11].

B. Finding Required Reserve Values

Once the power network is partitioned into zones, required reserves are determined using the percentage values defined in NREL's report [12]. This paper defines percentages for each type of reserve, such as regulation up, regulation down, spinning and non-spinning reserves. Tables 6, 7, and 8 in [12] provide required regulating, spinning and non-spinning reserves as a percentage of the peak MW demand.

TABLE I
RESERVE REQUIREMENTS (% OF PEAK DEMAND/MW) DEFINED IN [12]

Type of Reserve	ERCOT	SPP	MISO
Regulating Up	0.48%	0.92%	0.35%
Regulating Down	0.42%	0.63%	0.35%
Spinning	3.76%	1.14%	0.61%
Non Spinning	2.21%	1.43%	0.92%

For each zone in the synthetic cases, each bus's annual peak MW demand is summed up to get the peak MW demand. The percentages defined in [12] are then applied to this summation to obtain the necessary real power reserves. Mathematically, this is shown below:

$$\begin{aligned} &Required\,MW\,reserve = \\ &\quad(\%\,of\,MW\,peak\,load)\times \\ &\quad(Sum\,of\,peak\,MW\,load\,of\,all\,buses\,in\,the\,zone) \end{aligned}$$

Calculating the required reactive power reserves involves looking at the reactive power versus voltage (QV) curves. Vmax and Vmin limits are considered as the emergency operating voltage limits defined by ERCOT i.e., 0.9 pu and 1.1 pu, respectively. From the clustered zones, a representative bus, called the pilot node, is chosen at which the QV curve is generated.

The authors in [13] define ways to choose a pilot node. An important criterion for this selection is that the bus should have a high short circuit MVA rating. The approach used in this paper is to identify one bus in each of the clustered zones that have the highest short circuit MVA rating. Then, AC power flow is solved for all transformer and line N-1 contingencies. Of all these cases, three scenarios with maximum voltage violations are selected.

For these three scenarios, QV curve analysis is performed, and the maximum injected reactive power is identified for the highest-rated short circuit MVA buses. As an example, this is illustrated for bus number 110128. Bus number 110128 is the highest-rated short circuit MVA for zone II of the Texas 7k-bus synthetic grid, which is introduced in the next section. After performing the QV curve analysis for the three worst cases with maximum voltage violations, the maximum and the minimum reactive power injections at this bus are identified using the ERCOT voltage limits.

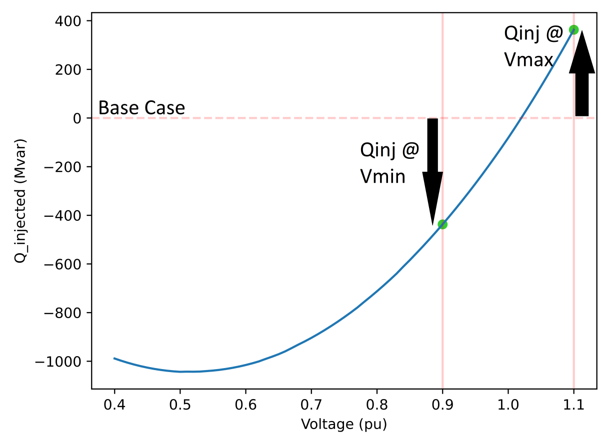


Fig. 1. QV curve for determining reserve requirements

III. CASE STUDY

Due to restrictions on accessing critical energy infrastructure information, the actual data on power grids are not available for research. Therefore, synthetic grids [14], which are created based on generation data from the U.S. Energy Information Association [15] and census data to estimate power load are used. More information on the creation of these grids are available in [16]–[18] and these realistic synthetic grids are validated based on the actual grids in [19] and [20].

A. Texas 7k-bus Synthetic Grid

The electric grid used in this study is a synthetic network geographically sited in Texas, U.S., and covers the geographic footprint of ERCOT with around 7000 buses. The 7k-bus synthetic grid is shown in Fig. 2. Bold green lines show the 345 kV transmission lines, 138 kV lines are shown in black and 69 kV lines with light green. Table II shows a summary of this case.

TABLE II
TEXAS SYNTHETIC GRID STATISTICS

Parameter	Numerical Value
Number of buses	6,717
Number of generators	731
Number of loads	5,095
Number of Switched Shunts	634
Number of substations	4,894
Number of transmission lines	7,173
Total design load (MW)	75,000
Total design generation (MW)	104,914

B. Midwest 24k-bus Synthetic Grid

The larger case study is Midwest 24k-bus synthetic grid over the US Midwest [21]. The transmission network is built based on the actual transmission voltage levels in this area, including 500 kV, 345 kV, 230 kV, 161 kV, 138 kV, 115 kV, and 69 kV.

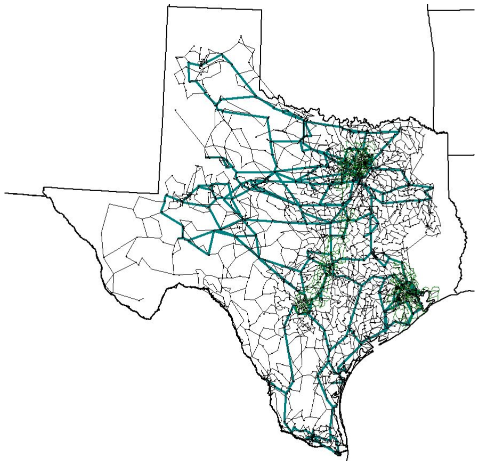


Fig. 2. Transmission lines of the synthetic Texas grid

Fig. 3 shows the one-line diagram on the transmission grid for Midwest 24k-bus synthetic grid where 500 kV lines and 345 kV are in green, 230 blue, 161, 138, 115, and 69 kV black. Table III provides a summary of the case.

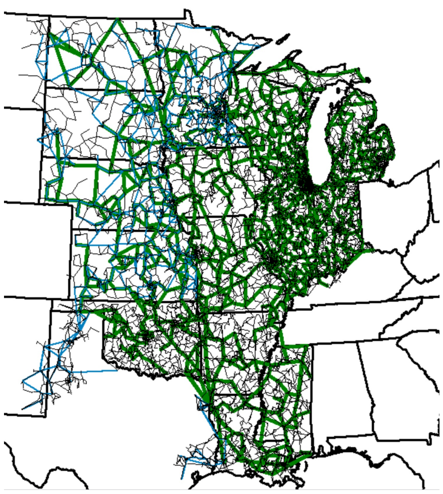
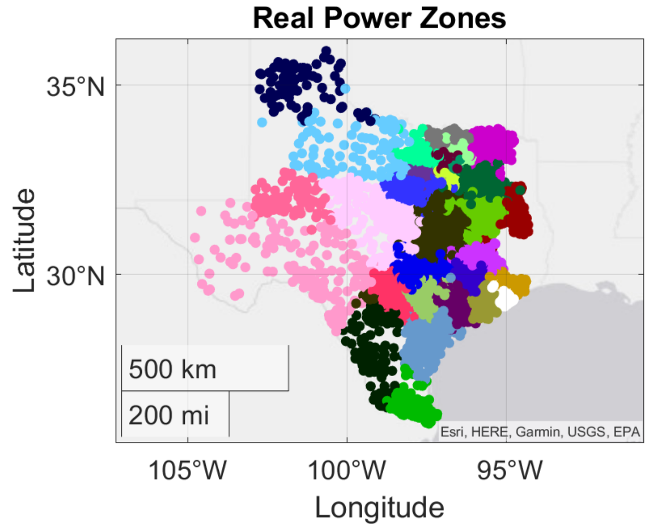


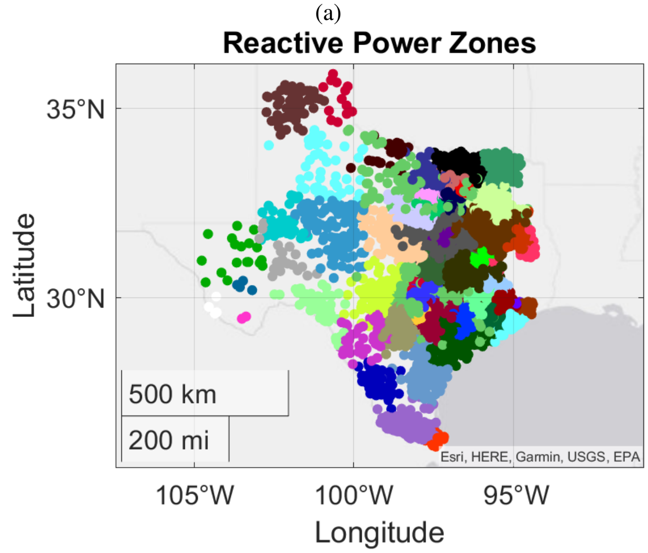
Fig. 3. Transmission lines in the synthetic Midwest grid

TABLE III
MIDWEST 24K-BUS CASE STATISTICS

Parameter	Numerical Value
Number of buses	23,643
Number of generators	6,274
Number of loads	11,731
Number of switched shunts	1,218
Number of substations	14,069
Number of transmission lines	23,787
Total design load (MW)	202,000
Total design generation (MW)	321,680



(a)



(b)

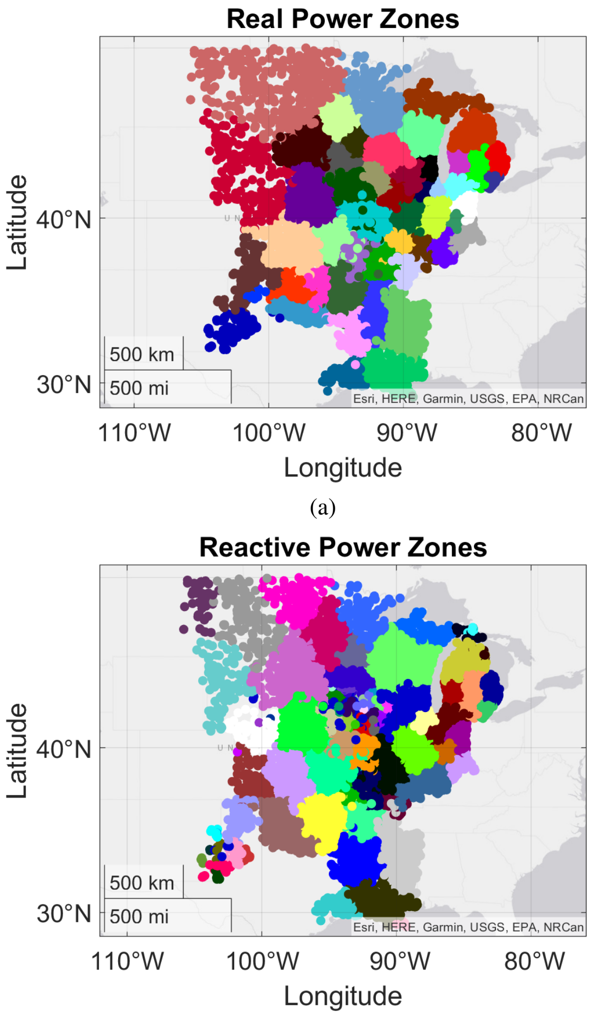
Fig. 4. (a) Real and (b) Reactive Power Zones for the Texas 7k Bus Case

IV. RESULTS

A. Clustering Large Scale Electric Grids Into Active and Reactive Power Reserve Zones

The results of the spectral clustering algorithm applied to the studied synthetic grids are shown in Fig. 4 and 5. All buses belong to only one cluster, and no two clusters intersect each other. A few zones far away from each other may appear to belong to one zone due to only a slight change in the hue of the color. Yet, these are completely different zones. Legends are omitted due to a lack of space due to a high number of clusters.

Table IV indicates the number of clusters chosen for each case. Table I shows the NREL-defined required reserve values for each area as a percentage of peak demand. [12]



(a)

(b)

Fig. 5. (a) Real and (b) Reactive Power Zones for the Midwest 24k Bus Case

TABLE IV
NUMBER OF CLUSTERS K PREDEFINED FOR EACH CASE

Synthetic Grid Case	Real power zones	Reactive power zones
7000 bus case	30	50
24,000 bus case	50	80

B. Finding Required Reserve Values

Using the methodology to find real and reactive power reserves specified in section II, the real and reactive power reserve zones for the Texas 7k-bus as well as the Midwest 24k-bus synthetic grids are calculated. For clarity, the calculation of required reserves for Zone I is explained. First, the peak annual demand is synthesized from the projected load data for the year of study, which is based on year 2016 in this case. Based on the NREL data [12], for each ISO, a required reserve is defined as a percentage of the peak annual MW demand. For zone I of the 7k case, the peak annual demand is 10347 MW. From I the required spinning reserve for the ERCOT region is 3.76% of the annual peak demand. Thus, the required spinning reserve for Zone I of the 7k case will be 389 MW.

In this paper, due to space constraints, only values for the first three zones are shown. However, this process is performed for all of zones, which their numbers are predefined in Table IV for the 7k-bus and the 24k-bus grids. For the 7k Texas case, the real and reactive power required reserves are shown in Tables V and VI, respectively. For the 24k Texas case, the real and reactive power required reserves are shown in Tables VII and VIII, respectively.

The results are not comparable across the synthetic case since they depend on the number of zones. The higher the number of zones, the smaller the required reserves for each zone. The number of zones selected for the 24k case is significantly higher than that elected for the 7k case. Since this paper utilizes the P-δ and the Q-V relationship from the Jacobian, these zones exhibit a strong correlation between these variables inside each zone.

TABLE V
REQUIRED REAL POWER RESERVE FOR THE FIRST 3 ZONES OF THE 7K CASE

Zone No.	Annual peak demand (MW)	Reg. Up (MW)	Reg. Down	Spin. (MW)	Non Spin. (MW)	Ramping (MW)
1	10347	50	43	389	229	207
2	10750	52	45	404	238	215
3	2666	13	11	100	59	53

TABLE VI
REQUIRED REACTIVE POWER RESERVE FOR THE FIRST 3 ZONES OF THE 7K CASE

Zone No.	Pilot Node	Nom kV	Vmax (pu)	Qinj at Vmax (Mvar)	Vmin (pu)	Qinj at Vmin (Mvar)
1	240317	13.80	1.1	197.89	0.9	-460.26
2	110128	138.00	1.1	345.17	0.9	-728.01
3	200204	18.00	1.1	97.64	0.9	-263.01

TABLE VII
REQUIRED REAL POWER RESERVE FOR THE FIRST 3 ZONES OF THE 24K CASE

Zone No.	Annual peak demand (MW)	Reg. Up (MW)	Reg. Down	Spin. (MW)	Non Spin. (MW)	Ramping (MW)
1	6190	30	26	232	136	124
2	1001	4.8	4.2	37.6	22	20
3	4599	22	19	173	101	91

V. SUMMARY AND FUTURE WORK

This paper presents a spectral clustering approach to partition large-scale electric grids into active and reactive power zones. It does so by leveraging the correlation between P-δ and Q-V, expressed in the Jacobian. The graph Laplacian is modified to include the Jacobian of a power network. Eigenvalues and eigenvectors are calculated, which are further used to partition the network into real power and reactive

TABLE VIII
REQUIRED REACTIVE POWER RESERVE FOR THE FIRST 3 ZONES OF THE 24K CASE

Zone No.	Pilot Node	Nom kV	Vmax (pu)	Qinj at Vmax (Mvar)	Vmin (pu)	Qinj at Vmin (Mvar)
1	120013	69	1.1	24	0.9	-112
2	170583	115	1.1	118.7	0.9	-91.6
3	250006	69	1.1	128	0.9	-136.6

power zones. Existing NREL standards are then used to determine the required reserve values for each zone.

Future work includes improving the methods of determining the number of zones and re-calculating the zones using the same spectral clustering approach. Additionally, simulations will be conducted to study the impact of the number of zones on the electrical and cost performance of the grid.

VI. ACKNOWLEDGEMENTS

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