A Method for Aggregating and Utilizing Distribution-Level Controllable Loads for Management of Transmission-Level Grid Security

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Abstract— This paper describes a method to aggregate multiple distribution-level residential/small commercial loads connect by single-phase/3-phase controllable "smart-meter" devices as portions of multiple transmission-level loads modeled in the regional Energy Management System (EMS). Utilizing clustering analysis of the modeled power system, zones are created where regulation of aggregated "smart-meter" connected loads may be employed to maintain grid-security. Employing transmission-level zone aggregations of these controllable loads, grid reliability coordinators are offered another tool to reduce congestion costs associated with dispatching generation to mitigate limiting transmission elements or peak loading.

Index Terms—ERCOT, Zone Determination, Load Aggregation

I. INTRODUCTION

THE most important purpose of Energy Management Systems (EMS) is to operate the transmission electric grid in a reliable manner. Those tasked with the operation of power grids (Regional Transmission Organizations RTO/Independent System Operators ISO) continuously work to ensure reliability by maintaining the grid at constant frequency in an N-1 secure state. "N-1 secure" is understood that a single event (loss of a single piece of transmission equipment, etc.) may not place the grid in an unsecure state by overloading any of the remaining pieces of transmission equipment that continue to be in operation. Additionally, there is always a need to maintain adequate generation on the system to continue meeting the current load, and thus ensure that grid frequency remains constant.

Traditionally, verifying security of the grid has been done by running powerflow simulations that study the effect of individual transmission elements (or multiple elements tied to a single point of failure) being removed from service, and the subsequent power flow solution indicating the lack of overloaded elements (this process is referred to as contingency analysis). If the powerflow solution indicates that post-

contingency overloading of one or more elements will occur, then the generation serving those loads is re-dispatched in a manner to remove post-contingency overloading for the affected elements. A powerflow solution with no post-contingency overloads is referred to as a security constrained solution. While many power flow solutions (differing generation dispatches) meet this criterion and will ensure reliability, from a market standpoint, efficiency is achieved by dispatching generation in the most cost-effective manner possible.

Meeting the criteria of a security constrained economic dispatch has customarily been done by the re-dispatching generation (raising output of lower cost generation and lowering output of higher cost generation) under the restriction of having enough generation to meet the load. While this is still the case in most situations, there are times when, from an economic or reliability sense, reducing the load can be a superior decision. This is true in a number of scenarios, such as in an emergency situation of a capacity constraining event (ice storm, hurricane, etc.) reducing available on-line generation, or on a system-wide basis where reducing the load could shave the peak demand, and reduce the need to bring more expensive generation on line for short term operations, or to reduce load in an import constrained area of the power-system where it is unrealistic to dispatch generation to mitigate.

In the past, these load resources have been limited to large industrial customers for several reasons. First, large industrial customers by definition have large loads and therefore are able to exact an effect on the transmission-level power system. Second, these large industrial loads have the ability to control the industrial processes that are consuming the power, i.e. raise, reduce, or even completely power down their loads. Third, from a purely record-keeping aspect, forming contracts with single entities that are directly responsible for their load was a relatively easy process to implement for those who were tasked monitoring and metering the load interconnection point to insure compliance and settlement. Finally, the nature of the large loads (single points of interconnection with the transmission level power system) allowed modeling as distinct points in the EMS allowing the ISO and RTO system operators to effectively dispatch the load as a system resource

without large software development costs (since this implementation leveraged heavily against existing EMS functionality).

Smart Grid initiatives that allow customers to control their energy usage at a more granular level and allow system operators additional tools in grid control are becoming more prevalent. As technological strides have been made, the feasibility of using widely dispersed small loads acting as a single aggregated dispatchable load resource is becoming realized. The availability of cheap, easy to install control systems, at a meter-level distribution for a residential load consumer, coupled with ubiquitousness of networked communications and small-scale interactive monitoring devices (applications for smart phones, tablet computers, etc.) piquing customer interests, have led to a point where small home-based loads commanded to respond in unison may produce the effect on the grid of the larger industrial loads that have traditionally been used in this manner. If these resources are to ever be utilized large-scale, a number of technological hurdles must be overcome.

One of the more pressing issues in this increased prevalence of smart meters, and corresponding consumer pressure to utilize the functionality as demand response, is a lack of granular modeling in RTO and ISO EMS's at lower voltage levels of the power distribution grid. In almost all cases, the cumulative effects of small dispersed loads are modeled as a single load point based on the interconnection to transmission level voltage of the line feeder. In many cases, the step-down distribution transformer is not modeled at all. This has been traditionally done for two reasons, one, insight into distribution level radial systems consisting primarily of residential and small commercial loads were not necessary for grid management, and two, adding that unnecessary level of granularity not only increased the amount of modeling work necessary, but also increased calculation times for EMS power flow solutions. Additionally, many of the common EMS systems have older computer architectures that are difficult to scale for additional data (table sizing).

The other, almost equally weighted, issue is the amount of effort required in any attempts to aggregate the multiple smart meters into a load sizable enough to be useful in grid control. With retail choice, load serving entities will be competing with traditional generation providing entities in moving to aggregate these meter owners with very little visibility into the physical realities of the transmission grid. Since these electric grids are, by and large, no longer vertically integrated (regulations prevent single companies from operating as a generation provider, transmission service provider and load serving entity within a single market), there is little opportunity for the transmission service providers to communicate or coordinate with the load aggregators. However, there is both regulatory pressure and financial incentive to implement these items as market product to the grid management system as soon as possible.

In this problem there are two competing matters. First, the realization that aggregating enough controllable-loads behind a single point of transmission level interconnection is problematic in implementation. It would be much easier for those who were trying to create an aggregated load resource to not have to worry as to which transmission load feeder is feeding individual households within a neighborhood. These aggregators will use a knock-on-door approach that will have little intentional correlation to areas of the gird where such resources will necessarily be useful. Competing with this is the necessity that RTO or ISO dispatching a resource, either load or generation, must know the location for security dispatching (but not necessarily for emergency system wide curtailment). While such granularity could be modeled into the EMS, at least in theory (modeling gradually into the distribution level) by expanding the database sizing and faster calculation performance, the long-term ability to maintain such a model is in doubt without significant increases in current RTO/ISO staffing levels.

Since maintaining such a robust model would be problematic, a different solution should be considered. In many retail markets, Transmission Service Providers track individual registered meters to at least the substation level. If an aggregating entity were able to present a list of individual meter load points to the transmission service provider, that service provider would know to which transmission-level modeled load that an individual meter was a component of, and be able to map accordingly. Hence, a list of participating smart meters, provided by load aggregators, could be separated, mapped, and then totaled up to a transmission level load point. This would allow some grouping of smart meters, however, the amount of load represented by an aggregating entity may still be small. To mitigate this concern, consider that resources that are accumulated behind modeled transmission-level loads (multiple load aggregators behind each modeled load, all with their own small load resources, based on their ability to register participants, etc.), that the transmission-level loads points themselves, could also be aggregated based on the electrical similarity of their point of transmission-level grid interconnection. These individually small load resources, collected with other load resources behind other loads, could be effective tools in grid management of what would essentially be zone-based aggregations. In general, these collections of load would have the following characteristics:

1) Located in a geographically concentrated area

2) Little or no internal transmission congestion and little chance of the condition changing over the course of time that the zone is in effect.

3) Smaller than what is thought of traditionally as load zones (may be 1000-10000 MW of load based on grid size for best granular control)

Based on these proposed constraints, this paper proposes a method to produce these transmission level zones, thus making it possible to utilize the smart meter controlled loads for various functions of grid control.

II. PROCESS

A. Base Case preparation

In order for a forward looking study to create transmission level zones it is necessary to study a power system base case (a mathematical model representing the power system, dispatched to a normal operating condition for a given load level). This case is normally transmitted via a flat text file referred to as a raw file (due to the file extension .raw), and is a standard file format developed by Power Technologies International (PTI), and is the de facto standard for representation of a bus-branch model. This format is compliant with a number of software vendors including Powerworld, PowerTech, and many others. Due to North American Electric Reliability Corporation (NERC) requirements ISO/RTOs are obligated to produce base case models for min and max load levels for five years into the future. Subjective judgment such as considering how often the zones will be reevaluated, market comfort with the amount of transmission equipment changes affecting transmission flows, etc. will determine which case is chosen for evaluation (or if a new case using different criteria is required). It is important that this case be modeled to a level of granularity to preclude non-modeled distribution interconnections between multiple points of modeled transmission level buses.

B. Selecting the Number of Competitive Zones

The decision on the number of competitive zones that the power grid will be divided into will be dependent on several parameters. A few important questions is how large do the areas need to be to be an effective tool in grid control, and to have effective competition among load aggregators. On the other side of the equation is how small an individual region can be made, since smaller zones will provide greater granular control of the system.

In order to separate the load into zones some parameter of the electrical system needs to be analyzed. In general, this parameter needs to be able to show differences between the power transmission characteristics of different points within the system. Three different parameters were considered: Power Transfer Distribution Factors (PTDF), Voltage Sensitivity (VS), and a total impedance measurement between points of transfer, however PTDF offered the best qualities for study that was conducted.

C. Power Transfer Distribution Factors (PTDF)

Power transfer distribution factors are the incremental distribution factors associated with electrical power transfers between regions of the system. In general, these power transfer distribution factors calculated from a point of study to a point of reference. DC lossless PTDFs are calculated in the following manner. First, a reference bus is chosen for the calculation. This reference bus needs to be in an electrically well connected area and dictates that the reference bus should be located at the highest voltage of the electrical transmission system in an area that has relatively low impedance and near the electrical center of the grid. Once this reference bus is chosen, for each point of measure in the grid, the following

actions need to be taken, a 1 p.u. load is placed at the reference bus, and a 1 p.u. point of injection is located at the other transfer location (electrical bus). The percentage of power flowing through every significant electrical element is then measured. This information may then be used to construct a matrix where each row represents an electrical transfer from a bus of study to the reference bus, and each column represents a transmission element in the system where power flows being measured. Once this matrix has been constructed the process for seeds to the next step.

D. Bus information reassignment

In order to reduce statistical noise, after the matrix has been constructed the following actions are taken. Every bus that exists as a radial end point in the system has its power transfer distribution factors overwritten with the power transfer distribution factors of its closest electrically connected bus. This process is then repeated with that next closest electrically connect at bus where its power transfer distribution factors will be overwritten by the next bus, and the process is repeated until the algorithm performing the tracing detects that the next closest in bus is non-radial, at which point the algorithm terminates. This has the effect of assigning every bus in a radially connected multi-section line group the same power transfer distribution factors as the first non-radially connected element in net multisession line.

E. Clustering.

Data clustering is a method by which objects may be grouped based on one or several variables. At a basic level it attempts to separate objects in groups, based on measurements or variables. This may be visualized in a matrix format where a total of p measurements per object are denoted as columns and a total of n objects are denoted as rows (measurements such as PTDFs, etc.). The j_{th} variable of the i_{th} object for a list of objects (total number of n) and with measurement values (v):

$$\text{objects} \begin{bmatrix} v_{1\,1} & \cdots & v_{1\,j} & \cdots & v_{1\,p} \\ \vdots & & \vdots & & \vdots \\ v_{i\,1} & \cdots & v_{i\,j} & \cdots & v_{i\,p} \\ \vdots & & \vdots & & \vdots \\ v_{n\,1} & \cdots & v_{n\,j} & \cdots & v_{n\,p} \end{bmatrix}$$

$$\text{measurements}$$

Fig. 1. Matrix Construction Raw Measurements

Once these variables are determined and the matrix is complete, a mean value (m) of each variable is determined by the following equation:

$$m_j = \frac{1}{n}\left(v_{1\,j} + v_{2\,j} + \cdots + v_{n\,j}\right)$$

Eq. 1. Mean value per measurement set

In this method the absolute mean deviation (mad) of each variable is calculated as follows:

$$\text{mad}_j = \frac{1}{n}\{|v_{1\,j} - m_j| + |v_{2\,j} - m_j| + \cdots + |v_{n\,j} - m_j|\}$$
Eq. 2. Absolute Mean Deviation

The individual measurements can then be standardized (x) in the following manor:

$$x_{i\,j} = \frac{v_{i\,j} - m_j}{\text{mad}_j}$$
Eq. 3. Standardized measurement

To yield the following standardized data matrix:

$$\text{objects} \begin{array}{c} \text{measurements} \\ \begin{bmatrix} x_{1\,1} & \cdots & x_{1\,j} & \cdots & x_{1\,p} \\ \vdots & & \vdots & & \vdots \\ x_{i\,1} & \cdots & x_{i\,j} & \cdots & x_{i\,p} \\ \vdots & & \vdots & & \vdots \\ x_{n\,1} & \cdots & x_{n\,j} & \cdots & x_{n\,p} \end{bmatrix} \end{array}$$
Fig. 2. Matrix Construction Standardized Measurements

Once the data has been standardized, the next step is to calculate the distance between every object in the system to every other object in the system, for true geometrical distance between points, the Euclidean distance (d) is calculated using the following equation:

$$d(i,k)$$
$$= \sqrt{(x_{i\,1} - x_{k\,1})^2 + \cdots + \left(x_{i\,j} - x_{k\,j}\right)^2 + \cdots + \left(x_{i\,p} - x_{k\,p}\right)^2}$$
Eq. 4. Euclidean distance

And the following matrix can be constructed, recognizing that a member of the diagonal $d(x,x)$ will be equal to zero:

$$\begin{array}{c} \text{objects} \\ \text{(1..i..n)} \end{array} \begin{array}{c} \text{objects} \\ \text{(1..i..n)} \\ \begin{bmatrix} 0 & \cdots & d(i,1) & \cdots & d(n,1) \\ \vdots & & \vdots & & \vdots \\ d(1,i) & \cdots & 0 & \cdots & d(n,i) \\ \vdots & & \vdots & & \vdots \\ d(1,n) & \cdots & d(i,n) & \cdots & 0 \end{bmatrix} \end{array}$$
Fig. 3. Matrix Construction inter-object distances

The matrix is symmetric about the diagonal because the distance from point A to point B is the same distance from point B to point A, only the lower triangle is necessary to reconstruct the entire dataset as shown in Figure 4.

Once these distances are known, a clustering partition algorithm will attempt to discover a representative object of each cluster, and then assigning each of the remaining objects to the nearest representative object, i.e. minimize the average distance from representative object to every other point in the cluster. Thru an iterative process that randomly seeds the cluster's representative object, and then applying the grouping function, followed by measuring the average distance from representative object to every object in the cluster, a good clustering solution will be determined.

$$\begin{array}{c} \text{objects} \\ \text{(2..i..n)} \end{array} \begin{array}{c} \text{objects} \\ \text{(1..j..n-1)} \\ \begin{bmatrix} d(1,2) & & & & \\ \vdots & & & & \\ d(1,i) & \cdots & d(j,i) & \cdots & \\ \vdots & & \vdots & & \\ d(1,n) & \cdots & d(j,n) & \cdots & d(n-1,n) \end{bmatrix} \end{array}$$
Fig. 4. Inter-object distances triangular matrix

III. RESULTS

Using the Electric Reliability Council of Texas (ERCOT) planning model for the summer of 2013, PTDFs are calculated using Powerworld software, where the electrical bus VENUS_N5 is designated as the reference bus (due to its centrality of the Dallas/Fort Worth Metroplex). A DC power transfer from electrically connected bus acting as a 1 p.u. injection source into the system and the reference bus acting as a 1 p.u. load is then simulated, and the branch loading is measured for every branch segment where voltages are greater than 120kV. There are 4724 branch segments in the studied model that meet this criterion. For example, the output from a PTDF measurement from bus WATSONCHPL (bus number 33) to the reference bus appears in Figure 5.

	From Number	To Number	Circuit	% PTDF From	Nom kV (Max)
1	1	4	1	-5.4278	138.0
2	1	964	1	5.4278	138.0
3	2	4	1	-17.3315	138.0
4	2	964	3	17.7621	138.0
5	4	9	1	-22.7593	138.0
6	9	25	1	-22.7593	138.0
7	25	47	1	-22.7593	138.0
8	31	36	1	-2.4375	69.0
9	31	38	1	2.4375	69.0
10	32	35	1	14.5747	138.0
11	32	37	1	-26.7171	138.0
12	32	64	1	12.1424	138.0
13	33	37	1	26.7171	138.0
14	33	47	1	27.5755	138.0
15	33	3394	1	45.7074	138.0
16	36	35	1	-3.0602	138.0
17	35	32897	1	11.5145	138.0
18	36	61	1	2.5522	69.0
19	38	32870	1	2.4375	69.0
20	43	48	1	-4.8162	69.0
21	43	93	1	2.8866	69.0
22	45	46	1	-5.4185	138.0
23	45	3597	1	5.4185	138.0
24	46	86	1	-5.4185	138.0
25	48	47	1	-4.8162	138.0

Fig. 5. PTDF Table, Branches are denoted by electrical bus connection points and a circuit ID.

As can be seen in the above table a power transfer out of the WATSONCHPL bus (33) leaves the bus along three separate paths (to buses 37, 47, and 3394) due to the physical characteristics of the electrical grid, and the sum of the transfers is equal to 100%.

This study is then repeated using every connected electrical bus (6550 buses). The data is then complied into a single matrix of 6550x4724 (approx. 31 million elements). This matrix is then clustered for 30 and 50 zones. It is noted here

that any number of zones maybe used, as the "correct" number will be one that both the stakeholders in the electrical market and operators responsible for reliability will settle at. These examples of 30 and 50 are meant to show the scalability of the process and some of the more interesting patterns that emerge with clustering greater numbers of zones. It is also noted that it is somewhat difficult to display results of a large geographic clustering analysis visually due to the decreasing variability in available color contrasting as the number of clustering groups increase. Figure 6 shows all zones with differing colors assigned to each bus. This map is not generally useful, except to give some very high level indications of zonal placement.
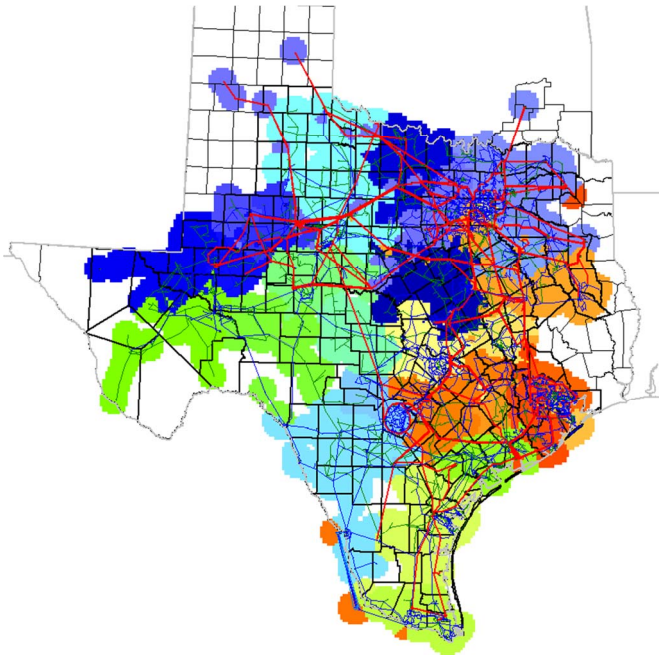

Fig. 6. 30 zone cluster map (all zones illustrated)

It is also useful to highlight only one zone at a time, to demonstrate this analysis, a medium size zone is highlighted in Figure 7, while all other zonal information is suppressed.
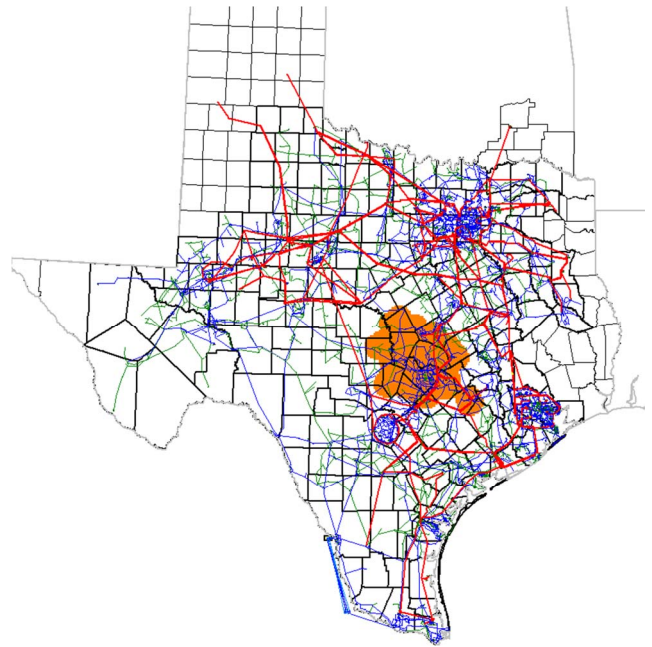

Fig. 7. 30 zone cluster map (single zone shown)

A data table showing the number of buses, amount of load, generation, line losses per zone and energy being imported is another useful method to display zone attributes. While the results of such grouping will always be somewhat subjective, an analysis shows that zonal geographic regions correlate highly with urban concentration and zonal boundaries correlate with service area tie lines.

Zone Num	# Connections	Load MW	Gen MW	Loss MW	Int MW
1	684	2101.43	703.28	33.49	-1431.63
2	494	947.15	887.69	25.50	-84.96
3	361	536.24	378.09	12.98	-171.13
4	333	522.10	1973.88	19.76	1432.02
5	356	568.74	829.17	10.85	249.58
6	70	88.29		1.56	-89.84
7	1626	6793.50	8084.66	136.98	1154.17
8	1820	9133.74	8652.11	265.48	-747.11
9	228	496.47	226.00	13.56	-284.03
10	630	5688.50	6259.01	70.16	500.36
11	463	1336.74	474.96	42.90	-904.68
12	651	750.15	194.56	23.87	-579.46
13	147	241.56	0.00	6.27	-247.83
14	399	439.08	312.18	20.45	-147.35
15	216	163.25	44.34	22.17	-141.08
16	276	274.53	225.15	7.74	-57.12
17	526	1751.94	2431.17	28.90	650.33
18	467	2498.34	1592.04	53.81	-960.11
19	646	2375.25	3521.54	79.54	1066.76
20	785	4722.69	6043.63	95.11	1225.83
21	315	1503.13	916.00	17.51	-604.64
22	237	742.12	721.00	12.01	-33.13
23	164	934.16	1418.84	9.73	474.96
24	551	3899.41	1753.80	28.55	-2174.17
25	1608	6868.67	10572.27	234.76	3468.84
26	123	144.12		7.27	-151.39
27	470	1900.49	1829.58	48.27	-119.18
28	90		0.00	0.01	-0.00
29	537	4855.29	5609.25	71.83	682.13
30	1220	12857.35	11115.49	232.36	-1974.23

Fig. 8. 30 zone cluster map (single zone shown)
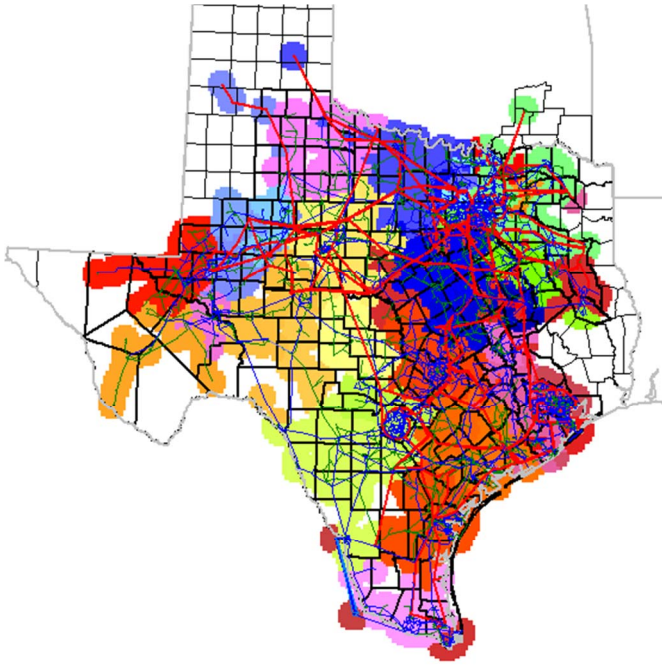
This process is easily scalable to 50 zones.

Fig. 9. 50 zone cluster map (all zones illustrated)

by load are still readily identifiable from Figure (8), indicating that this method highly weights toward tightly connected areas of the grid (in this case, corresponding to metropolitan areas). This method is also useful as a guide to illustrate which sections of the electrical grid are tightly coupled, as those would be the ones most persistent as zone clustering numbers increases.

IV. CONCLUSION

Clustering of an electric grid using Power Transfer Distribution Factors to create zones of aggregate multiple distribution-level manageable residential/small commercial loads as portions of multiple transmission-level loads provides a relatively simple method to allow the utilization of smart-meter technology to maintain grid-security. By utilizing these transmission-level zone aggregations, grid reliability coordinators are offered another tool for the operation of the transmission grid. This method is currently under study at ERCOT to weigh possibilities of implementation.

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Zone Num	# Connections	Load MW	Gen MW	Loss MW	Int MW
1	75	121.81		3.62	-125.42
2	387	1469.95		17.29	-1487.24
3	623	1895.68	1871.10	36.91	-61.49
4	21	58.14		0.24	-58.38
5	40	88.36		1.24	-89.60
6	732	1416.43	2561.79	51.68	1093.68
7	161	987.06	0.00	9.64	-996.70
8	341	522.10	1833.37	19.04	1292.23
9	76	94.25		1.73	-95.98
10	318	515.52	898.67	9.28	373.87
11	19	66.90		0.37	-67.27
12	182	1517.82		20.56	-1538.38
13	315	1503.13	916.00	17.51	-604.64
14	1635	8490.78	8652.11	256.96	-95.63
15	591	3322.21	1265.00	31.10	-2088.31
16	272	588.27	226.00	20.78	-383.05
17	33	179.76		0.93	-180.69
18	751	6399.37	7909.59	79.03	1431.20
19	467	1311.63	534.93	43.45	-820.15
20	139	209.15	0.00	6.07	-215.22
21	397	229.43	507.80	17.40	260.97
22	403	543.16	102.98	16.69	-456.87
23	56	33.06	32.29	10.97	-11.73
24	347	444.91	44.34	24.09	-424.65
25	99	122.61	0.00	3.65	-126.26
26	38	94.02		1.53	-95.55
27	23	33.51		0.04	-33.56
28	501	1208.92	1822.46	27.80	585.74
29	204	560.63	179.00	18.23	-399.86
30	618	2390.34	3150.48	80.57	679.57
31	931	5317.56	6043.63	112.82	613.25
32	17	67.42		0.66	-68.07
33	361	536.24	378.09	12.98	-171.13
34	79	253.92		5.14	-259.06
35	159	787.08	1418.84	9.34	622.42
36	81	334.81	480.00	9.10	136.08
37	440	2836.56	1435.01	20.47	-1422.02
38	245	1943.49	766.49	26.29	-1203.29
39	1236	4628.77	13960.13	242.95	9088.41
40	99	465.42	89.00	5.70	-382.12
41	86		0.00	0.00	0.00
42	472	4492.02	5161.55	70.38	599.15
43	98	1000.00	929.99	0.93	-70.95
44	96	598.40	608.71	2.23	8.08
45	1018	11298.64	9705.50	212.84	-1805.97
46	174	667.67	251.00	7.45	-424.12
47	177	151.92	225.15	4.09	69.14
48	239	164.51	194.56	5.22	24.83
49	209	1102.47	800.00	6.22	-308.69
50	412	2068.62	1814.13	50.20	-304.69

Fig. 10. 50 Zone Datatable

V. BIOGRAPHIES

John D. Moseley, P.E. is the Principal Engineer for Model Architecture and Integration at the Electric Reliability Council of Texas (ERCOT). John received his BSNE from the Texas A&M in 2000, and his MSEE from the University of Texas at Austin (2002). He is a registered professional engineer in Texas.

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Surya Santoso (M'96-SM'02) received the M.S.E. and Ph.D. degrees in Electrical and Computer Engineering from the University of Texas at Austin in 1994 and 1996, respectively. From 1997 to 2003, he was a Consulting Engineer with Electrotek Concepts. Currently, he is an Associate Professor in the same Department. His research interests include power quality, power systems, and wind power

Figure 10 (50 zone clustering) is interesting as a contrast to Figure 8 (30 zone clustering) in noting that with increased number of zones, only outlier buses are stripped from any given zone, i.e. note that in the Figure (10) the largest zones