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Morphological Image Analysis of Transmission Systems

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***Abstract*—This paper proposes morphological decimation of power network images for the purpose of analysis. The method creates a graphical image of a power network with a thickness of lines proportional to their respective rated megavolt-ampere capacity. Through morphological tools, the network image is decimated. This decimation process eliminates weak lines. Thus, strongly connected subnetworks emerge. This method of identification of several strongly connected subnetworks in a large network is tested on an IEEE test system. The method provides a quick bird's eye view of the strong subnetworks in a power system. Creation and decimation of network images to analyze other facets of the transmission system are also presented and discussed.**

***Index Terms*—Image processing, interconnected power systems, power system monitoring, power system planning.**

I. INTRODUCTION

MODERN power networks are large and complex. They are multilayered with different voltage levels. Several methods for tracing the flow of power have been reported in the literature [1]. The power network planner has a bird's eye view of the network. Through this intuitive bird's eye view, one may be able to isolate strongly connected subnetworks. Such a feel is vital in understanding the behavior of a power network under stress. Further, this understanding may also help the power network engineer to design and operate robust subnetworks in the event of emergencies popularly known as islanding schemes.

Thus, it is clear that there is a need for a tool that can capture power network data, and provide a clear visual representation and tools to visualize the strongly connected subnetworks. This paper sets about to do just the same. A single-line diagram of the power network is drawn such that the thickness of the line represents the rated megavolt-ampere (MVA) capacity of the line. This image is translated into a bitmap image. Thereafter, the bitmap image is decimated through a series of morphological transformations such that all of the lines composing the geometrical image of the single-line diagram are eroded. On successive *openings* through morphological transformations, thin lines with poor power transfer capacity get eroded and vanish. The thicker lines with good power transfer capacity are eroded and appear thinner. Thus, through a series of morphological transformations, the total network is broken and the subnetworks will emerge. Through this technique, a power network operator, planner, or a novice may quickly get a bird's eye view of a power network and its subnetworks.

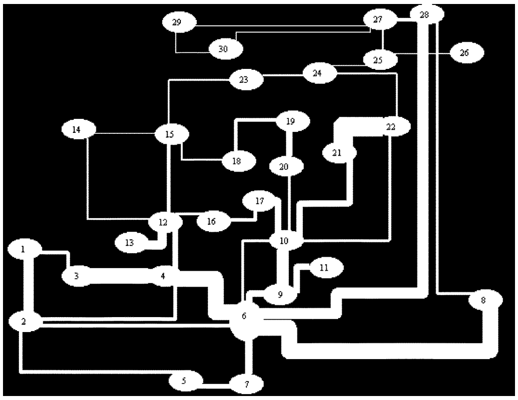

Fig. 1. IEEE 30-bus test network image.

This paper is organized as follows. Section II explains image construction considering power networks. Various methods of network image construction and their uses are detailed. Section III details mathematical morphology tools, basic transformations, multiscale transformations, and decimation processes using morphological tools. Section IV presents the test results on an IEEE test system and the results are discussed. Conclusions are given in Section V.

II. IMAGE CONSTRUCTION

This section details a simple method of image construction. It assumes that a single-line diagram for a power network is available. Rated MVA capacity of all the lines is used. Measures of other features of transmission lines may be adopted for image construction. They are enumerated and briefly discussed at the end of this section.

A. Image Construction Using Rated MVA Capacity of Lines

The IEEE 30-bus system was considered as an example. Using the rated MVA capacity of lines scaled appropriately, the widths of all of the 41 lines were computed. The single-line diagram of the 30-bus system was redrawn considering the line widths. Such a network image is shown in Fig. 1. This simple procedure may be adopted to draw the image of any system while representing the lines with widths proportional to its rated MVA capacity. Other methods of network representation are discussed in the following section.

B. Other Methods of Image Construction

Network image can be used to represent any facet of the power system that needs to be analyzed. Measures of any feature of the lines of the network may be selected for analysis. The network

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image is then constructed such that the width of the lines is proportional to the selected feature. On decimation, the thinner lines will vanish and thicker ones will appear thinner. The decimated image will bring forward those parts of the network that have a higher value of the selected feature of the network being analyzed. One may choose any of the following characteristics [2].

1) Operational Parameter Based Network Images: One may consider the following operational parameters and estimate the same for every line of the network. The width of the lines is set proportional to the selected parameter and the network image is constructed. These operational parameters may be one or a combination of the following:

- megawatt (MW) loss in the lines;
- Mvar loss in the lines;
- voltage gradient across the lines;
- phase-angle change across the lines;
- MW flow in the lines;
- Mvar flow in the lines;
- MVA flow expressed as a percentage of line rating.

An image constructed with line widths proportional to MW/Mvar loss and its decimation would bring out the lines causing higher losses in the system. This can aid in the analysis and, thus, planning of additional lines such that the accumulated costs from the energy losses are reduced. A voltage-drop-based network image and its decimation would bring out the lines that require additional var support. MW/Mvar flow-based images and their decimation would help in understanding the power-flow patterns in the system. Image constructed with line widths representing megavolt-ampere flow, expressed as a percentage of their rated capacity and its decimation, would bring out the lines that would require augmentation in the near future.

2) Maximum Capacity Based Network Image: One may select any of the following maximum capacity estimates of every line of the network. The width of the lines is set proportional to the estimated maximum capacity. The network image is then constructed. These parameters may be

- maximum power transfer through the line before the line suffers voltage collapse;
- maximum power transfer considering $\mathrm{I}^2\mathrm{R}$ limit;
- maximum power transfer considering angle stability limit.

The decimation of the network image so created would help in identifying lines that are weak and may cause collapse.

3) Other Representations: One may also visualize other applications for the proposed method. They are briefly alluded below.

- Instead of choosing to evaluate the lines that connect the busses of the network, one may elect to represent busses with thickness based upon the loads they deliver. Decimation of such a network image would identify load centers of the power network.
- Choice of representing busses having lower voltages with thicker images and decimation of such an image would help identify low-voltage pockets. Such an analysis may help in intelligent var planning methods in a power network.

III. IMAGE DECIMATION

The image drawn through the process explained in Section II yields a bitmap image of the power grid. This image directly does not bring out the weakly connected network links and neither do they provide means to directly assess the strongly connected subnetworks. In order to have a systematic procedure, morphological transformations are used to "decimate" the bitmap image of the power grid and extract the images of strongly connected subnetworks. Through the decimation process, the weak links (lines with small power transfer capacities) vanish.

The decimation process uses few morphological transformations. In order to understand the decimation process, a brief introduction to the morphological transformation and tools is presented in this section. It is followed by the detailed procedure of transformation used to decimate power network images.

A. Introduction to Morphological Transformations

Mathematical morphology is a field that offers many robust tools for extracting image components that are useful for representation and description. This field was originally developed by Serra [3]. It is a set-theoretic method of image analysis providing a quantitative description of geometrical structures. Morphology can provide boundaries of objects, their skeletons, and their convex hulls. The ultimate aim in a large number of image processing applications is to extract important features from image data, from which a description, interpretation, or understanding of the topology of the image can be obtained. These features can be edges and boundaries, shape features, spatial features, transform features, network features, etc. It is also useful in many pre- and post-processing techniques, especially in edge thinning or to identify subnetworks.

A power network that is represented as a binary image admits values 1s (power network points) and 0s (no-network points). In other words, the network and no-network points are respectively termed as set ($\mathbf{X}$) and set complement ($\mathbf{X}^{\mathbf{c}}$). The core principle of mathematical morphology is to compare *the object of* network $\mathbf{X}$ with a reference object $\mathbf{B}$, structuring element, with certain characteristic information such as shape, size, origin, and orientation. This structuring element is used to perform morphological transformations on discrete power network image data using different algebraic combinations. With the addition of some syntactic representations, the shape decomposition can proceed to form a unique representation of the data. The four basic morphological transformations are dilation, erosion, cascade of erosion-dilation (opening), and cascade of dilation-erosion (closing). From the point of segmenting the network into subnetworks that may provide a basis to classify the zones into strong and weak, the basic morphological transformations are defined as follows.

1) Erosion: The erosion transformation of $\mathbf{X}$ by $\mathbf{B}$ is defined as the set of points x such that the translated $\mathbf{B}_\mathbf{x}$ is contained in $\mathbf{X}$ and is expressed as below

$$\mathbf{X} \ominus \mathbf{B} = \{\mathbf{x} | \mathbf{B}_\mathbf{x} \subseteq \mathbf{X}\}. \quad (1)$$

Erosion operation shrinks the network. The degree of required shrinking and the direction of the shrinking can be controlled by defining the characteristics of the structuring element. If we

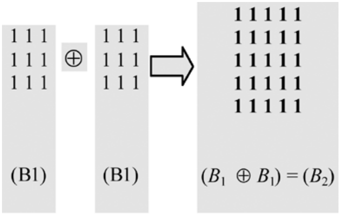

Fig. 2. Structuring element of size 3 × 3, square shape, with origin as center. Two elements of size 3 × 3 become a larger structuring element of size 5 × 5.

reduce the size of the structuring element, the "harshness" of the erosion process reduces. Alternatively, various degrees of shrinking can be achieved by performing iterative erosions by considering the primitive element.

2) Dilation: The dilation transformation of $\mathbf{X}$ by $\mathbf{B}$ is defined as the set of points x such that the intersection of the translated structuring element $\mathbf{B_x}$ and image $\mathbf{X}$ is not a null set

$$\mathbf{X} \oplus \mathbf{B} = \{x \mid \mathbf{B}_x \cap \mathbf{X} \neq \phi\}. \qquad (2)$$

This transformation widens the network segments. Use of a simple structuring element (all ones) makes the network segments wider and the network complementary space thinner. In general, the dilation process causes network widening to any desired degree which can be controlled by altering the characteristic information of $\mathbf{B}$.

In (1) and (2), $\mathbf{X}$, $\mathbf{X^c}$, and $\mathbf{B}$ represent network, no-network, and the structuring element, respectively. It is obvious that the no-network region expands during the erosion process. In contrast, during the process of network dilation, the no-network region shrinks. These are dual transformations. These transformation processes shrink and enlarge the power network segments. During the erosion transformations, the small no-network regions will merge and the thinner network segments will vanish. Alternatively, the neighboring network segments will be connected under continuous dilation process.

To perform large size erosion or dilation, these transformation processes can be iterated. Instead of using a larger $\mathbf{B}$, with the use of smaller $\mathbf{B}$ repeatedly one will get the same effect. The cumulative $\mathbf{B}$, of which the diagrammatic representation is shown in Fig. 2, is mathematically represented as below with n as the discrete size parameter

$$n\mathbf{B} = \underbrace{\mathbf{B} \oplus \mathbf{B} \oplus \mathbf{B} \oplus \mathbf{B} \oplus \cdots\cdots\cdots \oplus \mathbf{B}}_{n \text{ times}}. \qquad (3)$$

Successive n-times erosions (or dilations) can be represented as $(\mathbf{X} \ominus \boldsymbol{B_n})$ (or $(\mathbf{X} \oplus \boldsymbol{B_n})$). By employing these two basic transformations, the two cascade processes namely, opening and closing transformations are defined as follows:

3) Opening: The multiscale opening of $\mathbf{X}$ by a structuring element $\mathbf{B}$ of size n is the combination of erosion followed by dilation by the structuring element $n\mathbf{B}$

$$\mathbf{X} \,\mathrm{o}\, n\mathbf{B} = (\mathbf{X} \ominus n\mathbf{B}) \oplus n\mathbf{B}, \qquad n = 1, 2, \ldots, N. \qquad (4)$$

This transformation isolates thinner network segments and it may disconnect an aggregated network.

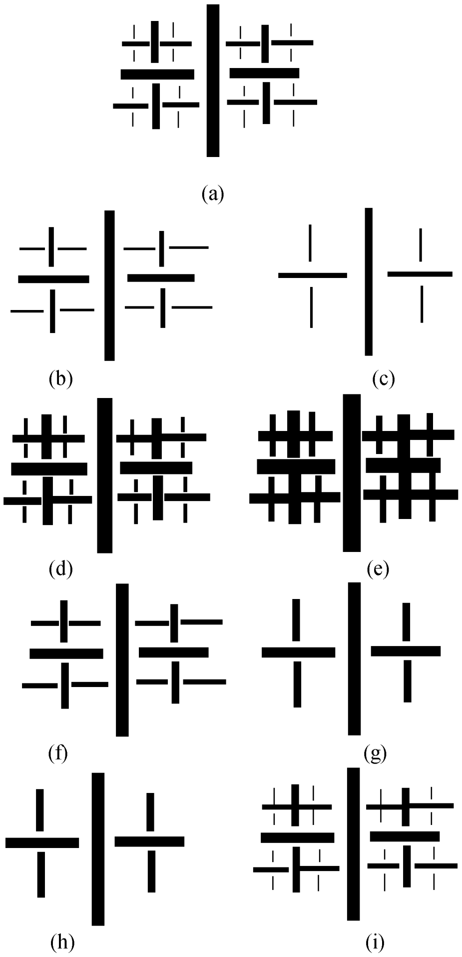
(a)
(b) (c)
(d) (e)
(f) (g)
(h) (i)

Fig. 3. (a) Synthetic power network with (black), and no-network zone (white background) depicting the network segments of various widths, (b) network after performing one cycle of erosion, (c) after two cycles of erosion, (d) after one cycle of dilation, (e) after two cycles of dilation, (f) after one cycle of opening, (g) after two cycles of opening, (h) after one cycle of closing, and (i) after two cycles of closing.

4) Closing: Closing of $\mathbf{X}$ by a structuring element $\mathbf{B}$ is dilation by $\mathrm{n}\mathbf{B}$ followed by erosion by $\mathrm{n}\mathbf{B}$. Opened image *is the subset of main image but* main image is the subset of closed image

$$\mathbf{X} \bullet n\mathbf{B} = (\mathbf{X} \oplus n\mathbf{B}) \ominus n\mathbf{B}, \qquad n = 1, 2, \ldots, N. \qquad (5)$$

It fills the holes inside the particles, eliminates the small details by smoothening the boundary from the outside, and connects close particles. It is worth mentioning that these cascade processes are idempotent when $n = 1$. With $n \geq 2$, these transformations, also known as multiscale opening and closing, are nonidempotent. In the multiscale approach, the size of the structuring template will be increased from iteration to iteration.

The impact of these four basic transformations is shown on a synthetic power network image [Fig. 3(a)] that depicts network segments of various widths. The widths of respective segments in the network are related to a feature of the power network. The resultant discrete power network images that are generated by applying the above described transformations on the synthetic power network of Fig. 3(a) are shown in Fig. 3(b)–(i).

B. Identification of Strong Network (Proposed Method)

To identify the stronger subnetworks in a large network, a procedure based on morphological tools is proposed. This procedure includes systematic use of multiscale *opening* on the given power network. The set of the morphological *opening*s of a power network by the sequence of structuring elements provides a great deal of information about the shape and size of a given network. It can also remove unwanted noise from the network. The process involves eroding a network, say n-times, and then dilating the network n-times. The idea being that the small structures or weaker lines (the size and shape determined by the structuring element) are completely eroded from the network so that only the large important objects or stronger lines remain to be dilated back to their original form. In the binary case, the *opening* by the structuring element $\mathbf{B}$ may be interpreted as the union of translations of $\mathbf{B}$ included in network. For example, the information derived from successive morphological *opening*s may be used to develop useful size distributions. It may also be utilized to provide a multiscale nonlinear smoothing of the boundary of a network. In this case, network image is considered to show the *opening* of the image. The same technique has been used to eliminate the weaker subnetworks from the power network image. The decimation process eliminates weak lines. Thus, strongly connected subnetworks emerge.

The following are the steps of image decimation:

1. Erode the image with morphological transformation for n iterations. The size of the structuring element is increased in each iterative step.
2. Dilate the image in n iterations with respective structuring element and size that were used while performing erosion.
3. At the end of n iterations, small structures or weaker lines are completely eroded from the network.

IV. RESULTS

In order to test the proposed algorithm, several different structuring elements have been tried. These were square, octagon, and rhombus-shaped elements. The octagon-shaped structuring element gave the best results. The IEEE 30-bus system was considered for the study. The image of the system was drawn with the thickness of lines proportional to their respective rated MVA capacity. In order to visualize the ability of the method, images using actual MVA flow obtained from power-flow analysis [4] and MVA flow in the lines expressed as a percentage of their respective MVA rating were also drawn and analyzed.

A. Image Created With MVA Rating of Lines

The image of the IEEE 30-bus test system is presented in Fig. 1. On processing the bitmap image of the system using the proposed algorithm, decimated images were obtained. The decimated image is presented in Fig. 4. The octagon-structuring element was used. On analyzing the decimated image of the system, it shows that the bus numbered 6 forms the center of the decimated subnetwork and the subnetwork consists of busses 6-4-3-8. Another two smaller subnetworks emerge and they comprise busses 1-2 and 21-22, respectively.

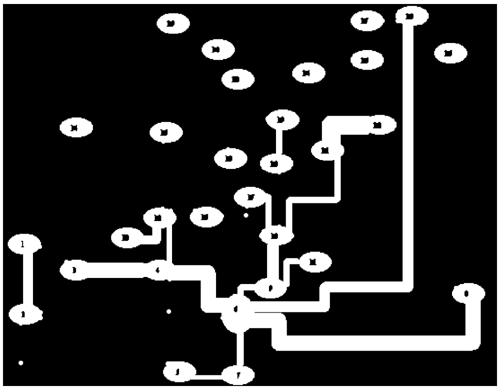

Fig. 4. Processed image created with MVA rating of lines.

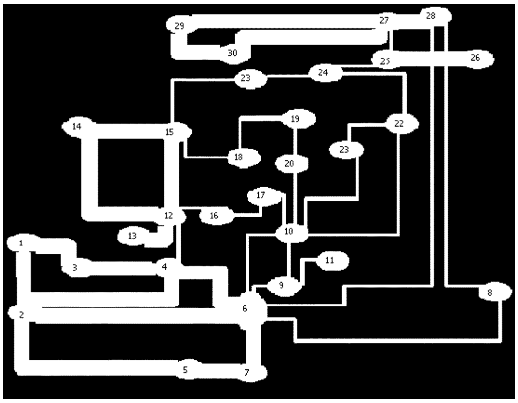

Fig. 5. Modified network image created with MVA rating of lines.

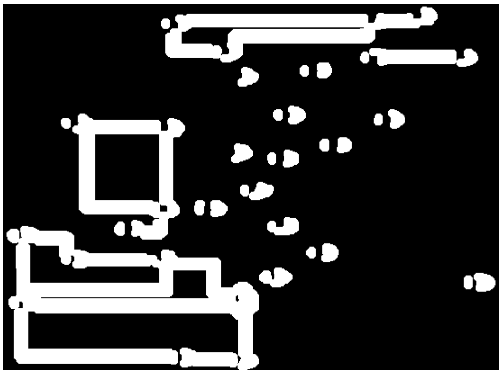

Fig. 6. Processed image of modified network created with MVA rating of lines.

B. Image Created With MVA Rating of Lines-Modified System

In order to visualize the proposed method better, the 30-bus test system line data was altered. The alteration was done in such a way that three clear subnetworks emerge after the decimation process. Fig. 5 presents the image of the modified network. Upon decimation of the full image of the modified 30-bus system, three clear subnetworks emerge as seen in Fig. 6. The three clear subnetworks comprise busses 1-2-3-4-5-6-7, 12-13-14-15, and 27-28-29-30. The octagon structuring element was used and the algorithm took four iterations.

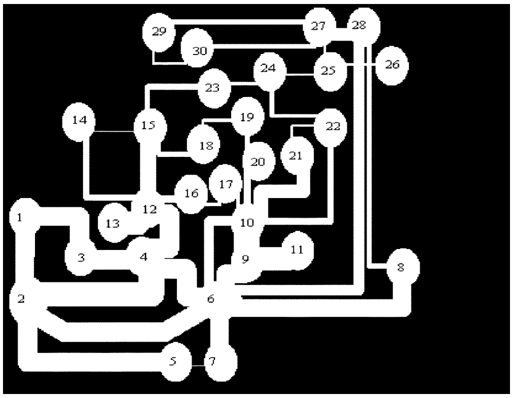

Fig. 7. Image created with MVA flow in line.

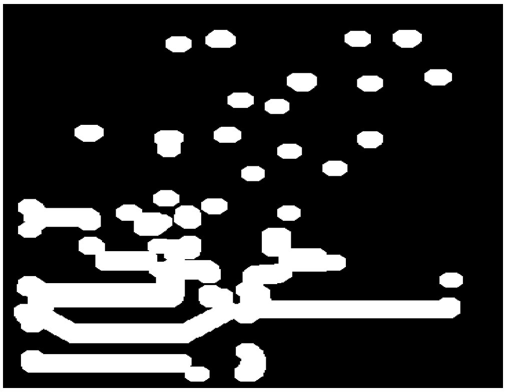

Fig. 8. Processed image created with MVA flow in line.

C. Image Created With Widths Proportional to MVA Flow

In order to visualize more applications of the proposed method, an image of the 30-bus system was created with line widths proportional to their respective MVA flows as given in Fig. 7. This image was decimated to identify strong flow patterns within the system. The decimated image is given in Fig. 8. This analysis helps us to identify the power-flow patterns within the system and coupling between generation and demand.

D. Image Created With % MVA Flows

Using the results of power-flow analysis, another image was created and analyzed. The image of the network was redrawn with a thickness of lines proportional to the MVA flow in the lines expressed as a percentage of their respective rating. This image is presented in Fig. 9. Upon decimation of this image, lines that were heavily loaded with respect to their rating remained while other lines that were underloaded with respect to their rating vanished as shown in Fig. 10. This exercise brings out the lines, which are loaded more. The results of the analysis also bring out the requirement of transmission system enhancement and related planning.

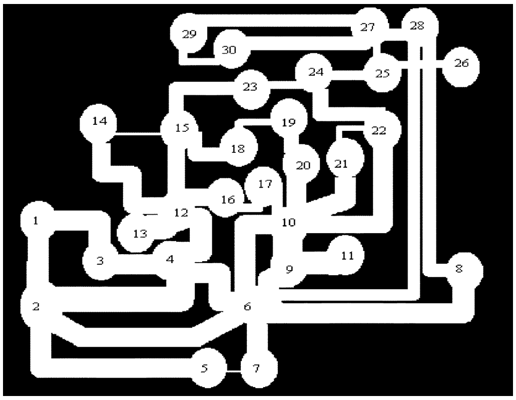

Fig. 9. Image created with percentage MVA flow in line.

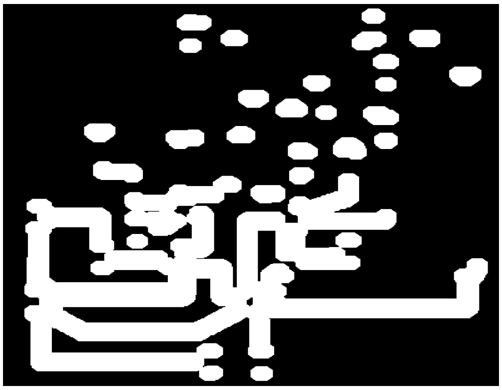

Fig. 10. Processed image created with percentage MVA flow in line.

V. CONCLUSION

This paper presents a scheme to generate a graphical image of a power network using rated capacity of lines. Other schemes of network representation using various aspects of transmission system are briefly discussed. A method to decimate the network to identify strongly connected subnetworks is presented. Through the use of this method, planners, operators, and novices may easily visualize the functioning of the network. Such knowledge may help to predict the behavior of the network. Results of the method applied to different facets of the network show that abstract information of the transmission system can be easily extracted. Through such a technique, proper islanding schemes may be developed. This technique may also help the planner to identify weak links in the network and strong subnetworks.

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