Novel autonomous lifting of a guyed V-tower: A case study

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The construction of overhead power lines in the Extra High Voltage category is a costly business. When erecting towers that support the conductors, mobile cranes have become the dominant piece of equipment to erect these towers. Although relatively quick, these mobile cranes do come at a cost and alternative erection methods will be very attractive for contractors responsible for construction. This paper investigates alternative options to erect overhead power line towers with specific emphasis on the use of gin poles and winches for the erection of the type 520B guyed V-tower thereby eliminating mobile cranes. The work presented here also proposes the use of novel methods like air cushions and a degree of automation to lift these guyed V-towers autonomously. Scale modelling is used to confirm experimental findings of the study.

Keywords: gin poles, guyed V-tower, mobile cranes, overhead power lines, winches, lifting air cushions

Die outomatiese oprigting van ʼn kabelgesteunde V-vormige kragtoevoertoring: ʼn Gevallestudie: Die konstruksie van oorhoofse kraglyne, en veral dié wat as “ekstra hoë spanning” gekategoriseer word, is ʼn duur besigheid. Met die oprigting van torings wat die geleiers ondersteun het mobiele hyskrane ʼn dominante stuk toerusting geword. Alhoewel hierdie metode relatief vinnig is, kom dit teen ʼn baie hoë prys. Daarom sal alternatiewe, goedkoper konstruksiemetodes verseker baie meer aantreklik lyk vir die kontrakteurs wie verantwoordelik dit is vir sodanige konstruksie. Hierdie artikel ondersoek alternatiewe opsies om oorhoofse kraglyntorings op te rig. Klem word gelê op die gebruik van nutspale (‘gin poles’) en wen-asse (‘winches’) vir die oprigting van die tipe 520B kabelgesteunde V-toring sodat mobiele hyskrane heeltemal uitgeskakel kan word. Die werk wat hier aangebied word, stel ook voor dat ʼn lugkussing as ʼn outomatiese metode gebruik kan word om die 520B kabelgesteunde V-torings op te lig.

Sleutelwoorde: Nutspale, kabelgesteunde V-toring, mobiele hyskrane, wen-as, lugkussings

Introduction

Contractors and utilities responsible for constructing overhead lines (ranging from 132 kV to 765 kV) and in particular in the EHV (Extra High Voltage) category of 400 kV and 765 kV normally use mobile cranes to erect the towers that support the conductors. Crane sizes vary from 70 ton capacity up to 250 ton depending on the line voltage and subsequent tower size (mass and height). Often, due to the height of the towers, a bigger capacity crane is required simply to achieve the required reach (height) without using the crane to its limit in terms of lifting capacity which in turn adds unnecessary costs considering the relative low mass of the tower lifted. Since the costing model of mobile cranes is such that a fee is charged whether the crane is used or not for the total rental period of the crane, it is therefore clear that if alternative erection methods that eliminate the use of mobile cranes can be developed, potential large cost savings can be realised. Even if mobile cranes are owned, their maintenance and operation costs are typically biggest compared to other construction equipment required for building overhead lines. This study proposes such alternatives.

Current construction practices

In South Africa, most of the 31 000 km (Eskom, 2016) overhead power lines that are built in the 132 kV up to 765 kV range consist of lattice steel towers which are used to support the conductor bundles. The lattice steel towers can be divided into strain and suspension type towers where suspension towers can further be categorised in self-supporting or guyed type suspension towers. Suspension type towers are used more in quantity on a line and it is here where the biggest potential economic benefit lies during the lifting operation. This study focus on the tallest 520B type guyed V-tower suitable for 400 kV applications which is used widely by Eskom, the power utility in South Africa. An example of such a tower can be seen in Figure 1.

Different methods (Kiessling et al., 2003) are currently employed to lift the 520B tower but the most common methodology involves a crane big enough in terms of reach to lift the complete assembled tower in one operation from the horizontal position to its final vertical position. Prior to lifting, the tower is constructed in one piece and aligned with the direction of the overhead line and with the tower top close to the tower foundation. The crane is positioned close to the foundation while the two legs of the tower are temporarily joined and put on a sledge or set of wheels so that, while the top part is lifted, the legs will slide towards the crane and foundation. Once the tower is upright it is positioned onto its foundation and the permanent guy ropes attached to the guy anchors and tightened. Plumbness of the tower is checked and the guy ropes are tensioned to their final preloads. Workers then ascend the tower after which the crane is disconnected before it can re-deploy to the next tower position. Progress on site is therefore limited to the number of cranes deployed to site as well as time taken for a mobile crane to get from one tower position to another. Often road conditions are poor and due to their size and mass cranes can get stuck very easily which all contributes to delays in work and undesirable progress. Therefore, if equipment to lift these towers can be more mobile and lighter and be duplicated more easily to perform many tower lifts in parallel, great cost savings could be realised and hence the current investigation into alternative erection methods is justified.

FIGURE 1: A type 520B guyed V-tower

An Alternative Method

By using gin poles and hoisting winches in a suitable configuration and layout, the alternative basic methodology can be seen in Figures 2 and 3. In brief it entails the following order of construction. The 520B guyed V-tower is assembled complete on the ground with the tower bottom as close as possible to its foundation and in-line with the running direction of the overhead line. A hinge mechanism will be positioned with jacks over the tower foundation and the tower bottom will in turn be attached to the hinge mechanism. The hinge mechanism will be securely anchored. The height and position of gin pole as well as position of winches need to be determined and positioned in accordance with a numerical "tool" that will determine the safe position and size of equipment required for the operation. Any temporary anchor points are positioned. All the lifting ropes are attached and the necessary sensors like load cells, angle inclinometers and accelerometers are attached to a control system. Lifting can now commence by the main winch while secondary winches will ensure stability of the tower during the lifting process under command of the control system.

The control system will use input data like tensions in the different ropes, rate of lift and angle of tilt and will control the winches to maintain a stable and safe lift. This part of the lifting process will happen autonomously without any human input except to keep a watchful eye to interrupt or stop the lifting process in case of emergency. Once the tower is upright, workers will use jacks to lower the tower onto its foundation, the permanent guy ropes will be attached to their anchors and the hinge mechanism removed. Workers can then disconnect all other construction ropes and equipment and move on to the next tower.

Study of the Basic Lifting Method

As a starting point, the most basic configuration of lifting a tower is explored. This entails placing the tower in the horizontal position and support points, simulating the top attachment point of a gin pole, at a position higher than the tower and a short distance away from the tower foundation. The first goal is to determine the minimum height of gin pole required to not load any member(s) of the tower more than 80% (SANS, 2017) of its capacity during the lifting process and to determine the magnitude of forces acting on the tower foundation, gin pole foundation(s) and in the various ropes required for lifting and stabilising the set-up. The software program PLS Tower is used to analyse the 520B guyed V-tower tilted 1° above its initial horizontal orientation. All the main and bracing members with their connections are modelled and when loads are applied, PLS Tower provides the user with an overview of the forces in each member as well as a percentage utilisation of the members based on their capacity in either tension or compression. The reason for the initial 1° tilt is to allow for small deflections and elongations in the construction ropes which bring the model at a starting position of close to horizontal prior to lifting. Figure 4 shows the basic set-up used in PLS Tower. In modelling the 520B tower the following key parameters are used;

- Tower height = 39.65 m (which is tallest version of the 520B tower)
- Conductor Attachment Height (CAH) = 33.0 m
- Tower mass = 7 960 kg

As an initial design, the gin pole is modelled using two fixed points at 14 m above ground and 10 m away from the foundation of the 520B tower. The values of 14 m and 10 m were chosen arbitrarily and based on construction experience in emergency restoration projects. The modelling of the gin pole in this simplified way is sufficient as the first objective is to confirm what minimum height of gin pole is required to not over load any tower members more than 80%. Apart from the mass of the tower to be lifted, provision is also made for the insulators and hardware to be lifted together as part of the tower (see C1, C2 and C3 in Figure 4). For this particular gin pole configuration, the key finding was determining the minimum value of angle α with reference to Figure 5.

It should be noted that there are many possible configurations and positions to set up a gin pole in order to do the lifting of the tower and the configuration in Figure 5 was used as a starting point as it resembles a very basic configuration. From the PLS Tower modelling analysis it revealed that if angle α is smaller than 11°, some members in the tower become over stressed due to the increase in horizontal or longitudinal forces as a result of the lifting action.

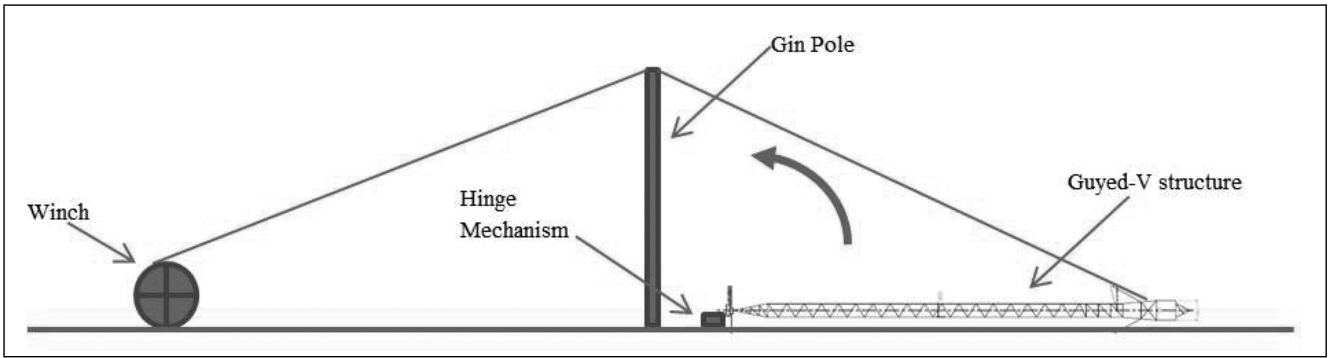


FIGURE 2: Side view of tower, gin pole and winches prior to lifting the tower

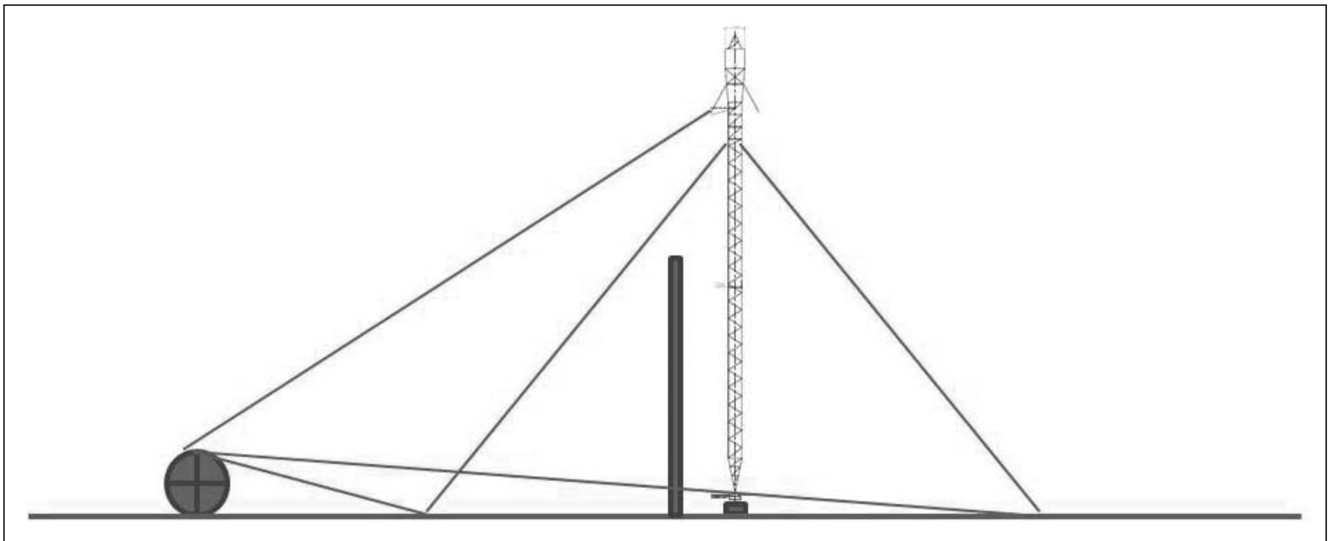


FIGURE 3: Final position of tower after lifting

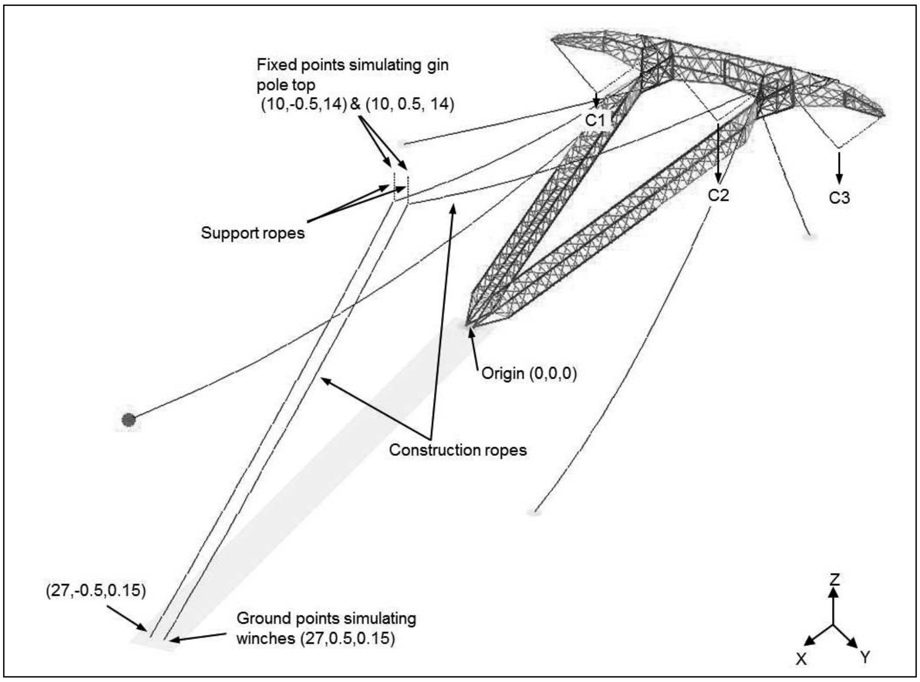


FIGURE 4: Basic PLS tower modelling of the 520B tower prior to lifting

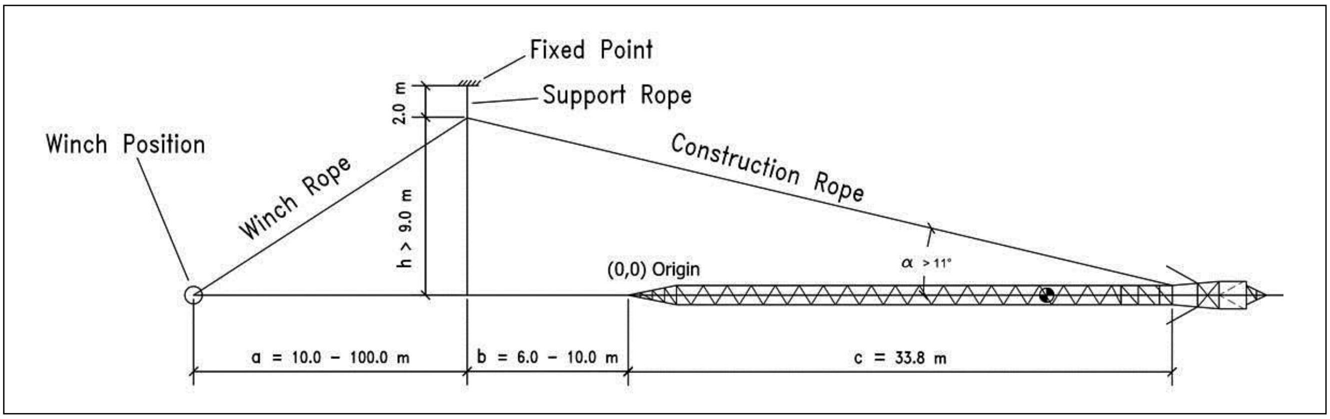


FIGURE 5: Key boundary conditions for using gin pole to lift type 520B guyed V-tower

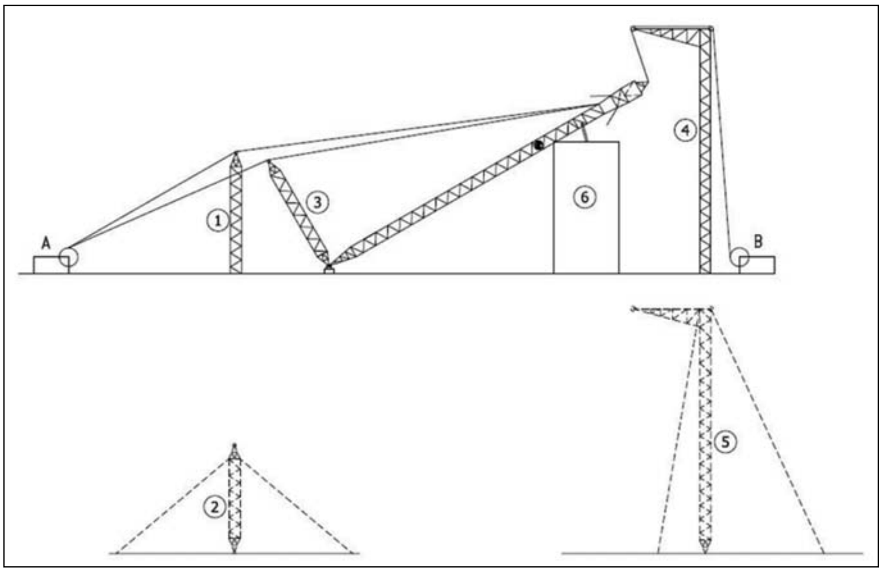


FIGURE 6: Six different lifting configurations compared

In a recent study by the first author (Jacobs et al., 2020) four gin pole lifting configurations together with two variations from two of the four configurations have been analysed in more detail providing a total of six different lifting configurations. Figure 6 shows the six different lifting configurations superimposed on one drawing that have been analysed and compared.

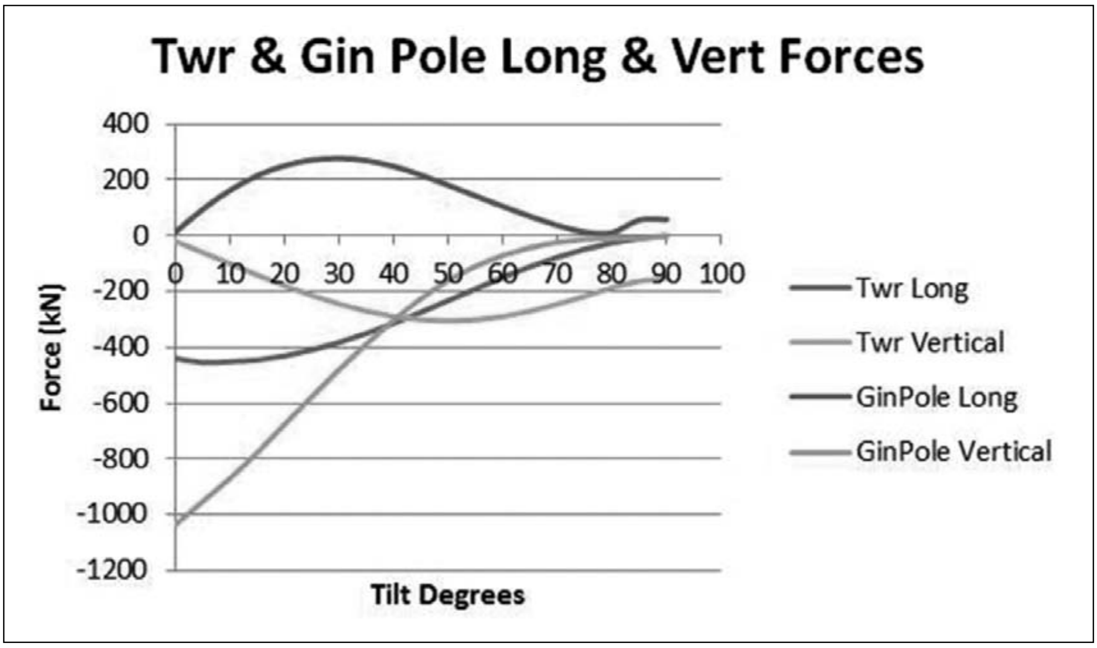
The 520B guyed V-tower is shown partly lifted in Figure 6 where option ① follows from the lifting configuration illustrated in Figures 4 and 5. Lifting configuration ① entails a gin pole that is self-supported and positioned a short distance away from the base and foundation of the tower. Lifting configuration ② uses guy ropes to keep the gin pole upright. Option ③ is also known as the "tilt-up" method (IEEE, 2009) of erection where the gin pole is positioned at the base of the tower. With option ④ the self-supporting gin pole is positioned on the opposite side of the tower where it will partially lift the tower before a second winch will continue the lifting process. Option ⑤ is a variation of option ④ where the gin pole is kept upright using guy ropes. Lifting configuration ⑥ uses an air cushion to partly lift the tower from where a winch will complete the lifting process. The study indicated that option ③ was the most feasible, closely followed by option ⑥ which utilises an air cushion. Hence, option ③ has been studied further yielding a suitable gin pole mast design and a suitable size winch.

Gin Pole and Hinge Mechanism

The gin pole mast is a key element in the lifting process and has to be strong enough to withstand the forces acting on it while at the same time be readily manoeuvrable, hence gin pole mass is a key consideration. Furthermore, for the tower to rotate from an initial horizontal position to its final vertical position, a hinge mechanism is required. In order to calculate the forces required to lift the tower and its reaction on the gin pole and hinge mechanism, PLS Tower was used to simulate the lifting process from an initial horizontal orientation of 0° to a final vertical orientation of 90° in increments of 5°. Since the lifting process is expected to be slow due to the general low speed that winches operate and possible use of lifting tackle to assist with the mechanical advantage, the suggested statically incremented simulation is relevant and acceptable. A similar approach was followed by (Van Zyl et al., 2006) where the analysis of a rotating tippler structure was evaluated in intervals of 10°.

The results can be seen in Graph 1 where the longitudinal direction is parallel with the overhead line. Note that the loads represented in Graph 1 were generated using the shortest possible gin pole mast of 9 m that can be used for angle α to be more than 11° as described earlier. The shortest gin pole also generates the highest forces since the mechanical advantage utilising such a gin pole is the least.

For the design of the hinge mechanism the results from Graph one were used as input and a triangular frame using standard available steel sections (Construction, 2010) was considered for the design. Graph one clearly indicates that for the initial tower lifting orientation of 0°, the peak forces are the Gin Pole Vertical and Tower (Twr) Longitudinal forces. Similar findings were made by Wood, 2007. Therefore, anchoring of the hinge mechanism frame to be able to withstand these (horizontal) Tower Longitudinal forces is of vital importance. A triangular hinge mechanism



GRAPH 1: PLS Tower calculated longitudinal and vertical loads versus tilt angle of the tower and gin pole

frame that supports a shaft which can slide vertically down, as it is controlled by hydraulic jacks, is proposed here (see Figure 7). The tower pivots around the shaft while being clamped by two removable brackets that interface with the bottom ends of the tower legs. Once the tower is pivoted upright, it gets lowered onto the tower foundation. Thereafter, the triangular frame is partly disassembled and can be moved to the next tower position to be used again.

The Air Cushion Concept

Air cushions are regularly used to lift and move heavy machinery and equipment by utilising the efficiency of the air bearings to move a load on a frictionless film of air. An example of such a system was investigated by Lisowski and Filo (Lisowski, Filo., 2011). A variation of this concept is the well-known hovercraft. Another application of air cushions is known as lifting bag or lifting cushions where the air is contained in a flexible container like a rubber bag normally of circular or square shape. Depending on the size and strength of the bag, the air can either be pumped in under high pressure, by means of a compressor, or be pumped in under low pressure by means of a blower. A variation of the last mentioned system that utilises a big area and low pressure to obtain lift can be found in the entertainment industry as jumping castles, water slides or space rockets. An example of water slides can be seen in Figure 8.

This same concept of low pressure air blown into a suitably shaped container with a triangular form can be utilised for lifting the 520B guyed V-tower as depicted in Figure 9.

The lifting process using the triangular shape air cushion will start by positioning the cushion under the tower on suitably prepared ground that is free from obstacles and sharp objects that can damage the cushion. Low pressure air blowers will be positioned and used to blow air into the cushion from a number of feeding points. The triangular cushion will be internally supported and divided into cells which will prevent collapsing of the side walls and be able to support the load. These different compartments will prevent total sudden collapse of the cushion even if one compartment or cell gets damaged. Depending on the size of cushion it would be theoretically possible to lift the tower to a sufficient height, eliminating the use of a gin pole all together, and only making use of a winch to lift the tower to its final upright position.

Potential economic viability of the alternative lifting method

The alternative "tilt-up" lifting method proposed here for the construction of overhead lines has been the focus for wind generator erection as well. In a study conducted by Ganser et al., 2014 it is concluded that the tilt-up method of construction for smaller residential wind turbines could

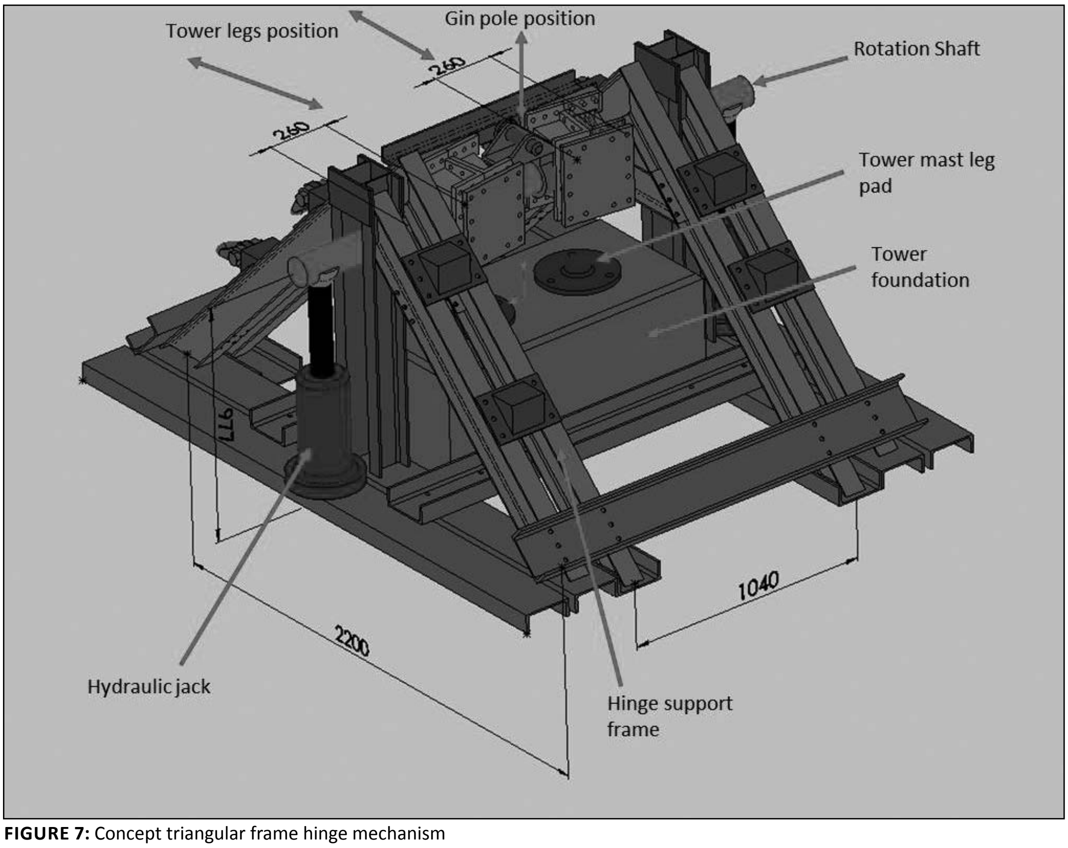


FIGURE 7: Concept triangular frame hinge mechanism

FIGURE 8: Example of low pressure air supported water slides

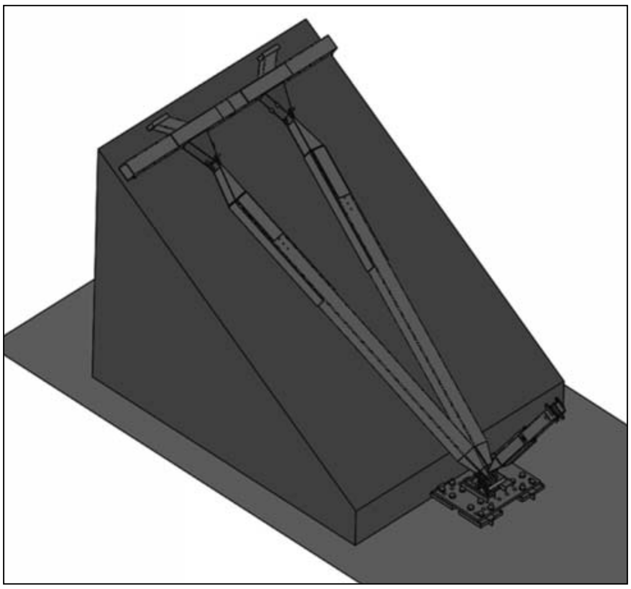


FIGURE 9: Concept of air cushion to lift type 520B guyed-V tower

present lower costs compared to traditional erection methods which utilise mobile cranes.

Another study conducted by Orrell, 2017 into the installation costs of wind turbines, some projects had minimal installation costs due to the tilt-up method which required very little labour and few tools.

Since the costing structure, that overhead line contractors responsible for building lines are using, is hard to come by due to the open and competitive market they operate in, some high level capital outlay comparisons are made. When considering the capital cost of a new 90 ton mobile crane, which is the minimum size normally used by contractors for lifting the 520B guyed V-tower, we can compare it to the capital cost of a winch and gin pole system as described here. It is estimated that the capital cost of a winch and gin pole will be approximately 25% of the capital cost of a 90 ton mobile crane.

Normally, "dressing" (Badenhorst, Marais, 2005) of the tower, which is a term used to refer to the attachment of insulators and hardware to the tower in preparation for the stringing operation, is done separately as a follow-up step once tower erection is completed. With this alternative lifting proposal, the dressing activity can be concluded before the lifting process since the insulators and hardware can be attached to the tower prior to lifting. This will save the time normally spent on lifting the insulators and hardware into position after the tower has been erected.

Another time saving factor would be the relatively easy transportation of the winch and gin pole system in comparison to relocating a mobile crane which is very often limited to the terrain in can operate in. In some cases the counter weights of a mobile crane have to be detached from the crane and transported separately in order to enable the crane to move more easily. Furthermore, when the winch and gin pole systems are duplicated, a number of towers could potentially be erected in parallel.

It is envisaged that the air cushion lifting concept will be more mobile and require less tools and equipment to operate, thereby realising even bigger savings compared to the use of a gin pole and winch.

Conclusions

There is a clear need to find other more economical methods to erect transmission towers. The use of gin poles and winches has, to date, not been implemented for this application and is investigated here for lifting a type 520B guyed V-tower. A comparison of six different lifting configurations using gin poles and winches was done in a previous study and the most suitable configuration is a gin pole positioned at the base of the tower connected to the same hinge mechanism as illustrated as option ③ in Figure 6. An unconventional air cushion lifting concept, which potentially can eliminate the use of a gin pole all together, will be studied in more detail going forward.

Potential big cost and time savings can be realised with the use of the proposed alternative lifting concept of using a gin pole and winch when compared to the traditional mobile crane method for lifting guyed V-towers.

The alternative lifting concept can be scaled up or down in order to, for example, lift similar guyed V suspension towers type 702B used on 765 kV overhead lines in South Africa. Similarly for lower voltage lines and where access to machinery like mobile cranes is difficult and expensive, this concept can offer a viable solution.

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