European Journal of Technique

journal homepage: https://dergipark.org.tr/en/pub/ejt

Vol.12, No.1, 2022

A Survey on Traction System Development of Automated Guided Vehicles

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ARTICLE INFO

Received: Jan., 04. 2021
Revised: Dec., 05. 2021
Accepted: Mar, 17. 2022

Keywords:
Automated Guided Vehicles (AGV)
Traction system topologies
Energy efficiency
AGV motors, inverters

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ISSN: *2536-5010* | e-ISSN: *2536-5134*

DOI: https://doi.org/10.36222/ejt.1002554

ABSTRACT

Abstract—Automated guided vehicles have been part of all production and logistic systems. Industry 4.0 technologies have also increased the applications of AGVs because of the demand for autonomous operations with minimum human power. In parallel to the growth of AGV market, researchers and application engineers need a holistic approach considering all aspects of development and application of AGVs.

Objective of this study is to provide guidelines for AGV development with focus on traction systems. Traction topologies, motor and inverter specifications, energy efficiency solutions, failure risks of AGV motors, and electrical system development issues are reviewed.

1. INTRODUCTION

Automated guided vehicles (AGVs) have been part of all production plants for the last 20 years. It is also one of the fastest-growing markets [1], as the demand for logistics and robot-operated automation systems are increasing. First generation of AGVs were developed as standalone vehicles. Second and third-generation AGVs have evolved into decentral control in terms of path planning, localization, and traffic management [2-5]. This evolution has been accelerated by the development of smart factories using the industry 4.0 technologies. The historical evolution of AGVs for different applications is given in [5].

In AGV literature, majority of the publications are on AGV control system software [2-4]. There are a few studies on traction and electrical system development. Therefore, the objective of this study is to review the conceptual development phases, integration and application aspects of the traction and electrical system of an AGV.

According to the market analysis reported in [6], the most common types of AGVs in the global market in 2020 are listed as below:

- Unit load carriers
- Automated forklift trucks
- Tow vehicles
- Assembly line vehicles
- Underride tunneling vehicles

Due to the variety of these applications, power components market can be expected to grow further in order to provide solutions at higher power levels. Power components of an AGV includes traction motor, inverter (motor control unit), gearbox, lithium based batteries, cabled or wireless (inductive) chargers and DC-DC converters.

48 V electrical system is commonly used in AGVs. There are AGV motor controllers rated at 1500 A current at 48 V DC input supply [7].

Contrary to the past use of 48 V supply for auxiliary systems in automotive applications, 48 V supplied motors, motor controllers and chargers are expected to have higher currents ratings in near future.

2. CONCEPTUAL DEVELOPMENT STEPS OF AN AGV PROJECT

2.1. Specifications and system configuration

The list given below refers to an AGV applied in automotive production and can be expanded into other AGV applications as well:

Step-1: Specifications and tasks related to the AGV operation environment

- Type of AGV
- Central or decentral control
- Localization and mapping method

- Positioning accuracy of AGV
- AGV speed
- Maximum inclination angle at the operation floor
- Maximum payload at maximum acceleration
- Safety and certification requirements

Step-2: Specifications and tasks related to the software development

- Configuration of the safety PLC software operating according to the outputs of the safety sensors
- Sensor selection and integration of drivers into the ROS (Robot Operating System).
- Configuration of task manager and path planner according to the operation environment
- Configuration of the traffic management system according to the operation environment

Step-3: Load related specifications

- Traction system topology
- Sizing of motors, gearbox and battery Ah capacity
- Radial forces per wheel at maximum payload

In this study, steps 1 and 2 are reviewed briefly. Step-3 and its relationship with step-1 and 2 is analyzed in detail.

3. INTEGRATION of AGV into FACTORY AUTOMATION

3.1. Compatibility with Industry 4.0

In this section, an overview of AGV technologies and technology selection criteria will be studied. Technology selection has a decisive impact on AGV lifetime and performance in the target application.

Industry 4.0 is a broad term specifying features of an intelligent factory environment where process efficiency and production outputs can be increased by software tools such as data processing, connectivity of process components, predictive maintenance, remote control etc.

In order to integrate an AGV into an industry 4.0 compatible factory, technological transformation is required as listed below:

1) Decentral control of AGVs

In decentral control, AGVs can autonomously plan their path and make decisions about their motions. Decentralized control methods are practical and scalable solution for large AGV fleet operations [2-4].

In [2], solution models for centralized and decentralized control are studied and importance of decentralized algorithms are emphasized as they provide open architecture, configurability, scalability, and robustness.

In decentralized architecture, AGVs can navigate independently within the defined AGV control tasks [3]. If the process requires a higher number of AGVs and complex tasks, the central control of AGV is not suitable as the central controller needs to re-define the path in case of a deviation from the planned path for each of the AGVs [2-4].

2) Use of digital twin modelling in AGV control

Digital twin (DT) a virtual model of a physical system. It has been studied recently in manufacturing systems for industry 4.0 compatibility. DT enables simulation and optimization of manufacturing system in a digital platform [8]. In development of AGVs, DT can be used to model the physical operation environment to develop navigation and localization software and test of operation safety as well [9-10].

3) Remote monitoring of AGV data

AGV control can be improved if operational states of AGV, faults and variables like energy consumption, battery state of charge (SOC) can be monitored remotely. Monitored data can be used to improve the task management, predictive maintenance and energy efficiency. DT modeling is an effective tool for AGV performance monitoring and optimization. Modeling and application examples from a smart factory model is studied in [11].

4) Charging method

Wireless charging technology, known as also inductive charging, enables charging of AGV at any location where transmitter pad of wireless charger is installed and thus eliminates cable and connector [5,12-13]. If charging and operation duty cycle times can be optimized, wireless charging can enable operation of AGV continuously without need for a cabled charging.

5) Cyber security of AGV

Despite the advantages of industry 4.0, the connectivity of components increases the risks of cyber-attacks which can cause uncontrolled stops. Case studies and solutions are studied in [14-16]. Use of 5G private network enables higher system security [17]. Digital twin modeling can also detect normal and cyber attacted operations in a smart factory [18].

6) 5G wireless network

Use of 5G wireless network (WN) for AGV control and fleet management is expected be the future trend [5,17]. 5G WN enables faster control of AGV and increase of production throughput as studied in [19].

3.2. Relationship between AGV subsystems

Overall Equipment Efficiency (OEE) is a production performance metric and studied in [20].

Fig.1 illustrates how the conceptual development phase can improve the overall performance of an AGV and key performance index (KPI) of the production as well.

Fig.2 illustrates the multidisciplinary engineering works for an AGV development. For an optimum development of an AGV, relationship between these engineering works should be carefully analysed at the conceptual development phase.

The following issues are listed to highlight the relationship between AGV subsystems:

1) Navigation methods, path planning and motor duty cycle:

The selected navigation method, path planning and operation environment will significantly influence the motor and battery duty cycle. Critical issue is to operate the motor at efficient operating points. For this purpose, the number of start and stop cycles can be reduced. Because every start needs an acceleration torque and causes higher power consumption than constant speed operation. If AGV path plan can enable operation at higher speed, this will also improve the AGV traction system efficiency. Therefore, navigation method, path plan and permissible motor duty cycle given in motor datasheet should be analysed together.

2) Importance of EMC/EMI in an AGV Fleet

The minimum distance between AGVs for collision avoidance is a design parameter for path planning algorithm. Additionally, when developing the path planning, potential EMI (electromagnetic interference) problems between AGVs should also be considered to avoid the EMI problems as well.

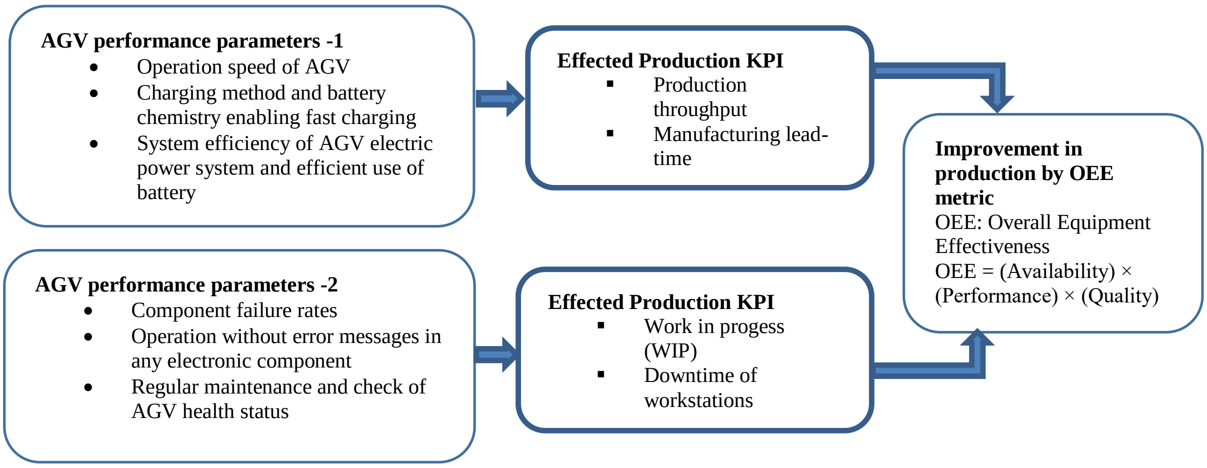

Figure 1. AGV performance parameters and improvement possibilities on process KPI (Key Performance Index)

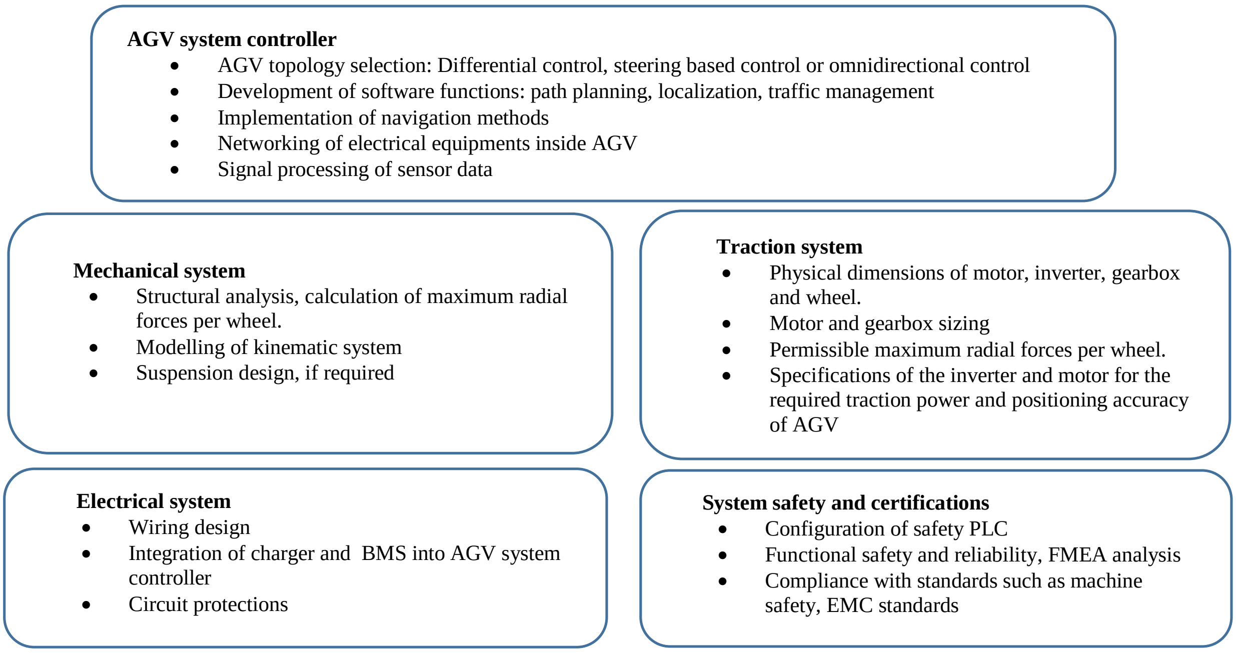

Figure 2. Main development steps of subsystems of an AGV

In [21], EMI risks and analysis is studied for battery electric vehicle in traffic that can create interference to vehicles nearby. Same risks are valid for AGVs.

3) Available battery energy and payload

AGV payload capacity for a predefined task can be estimated depending on the available battery energy. This type of estimation can prevent deep discharge of the battery and also prevent undesired stops of AGV during the operation.

4. CONCEPTUAL DEVELOPMENT OF AGV TRACTION SYSTEM

4.1. Relationship between traction topology and traction system specifications

Steering of an AGV can be realized either by differential control or steerable drive system. Steerable motor drive systems are commonly used if AGV has longer length (> 2m) and smaller turning radius is required. Some examples of commercially available steerable systems are given in [22-24]. Total system efficiency and maintenance requirements of steerable drive system should be discussed with the suppliers. The most common topologies and steered drive systems are listed below [22-25].

1. Two-wheels active steered, two wheels passive driven systems.
2. Steering system with two steered wheels and rotating 180 ° or 360 °.
3. Steerable drives designed as a compact system including one motor for steering and one motor for traction system.
4. Omnidirectional AGV which can move in all directions and rotate 360°. The number of wheels can be four or six.

Most of the AGVs used in automotive production plants can have a payload capacity between 600 kg and 3000 kg.

When selecting the AGV traction topology, the requirements for the following operation conditions should be defined:

1) Minimum radius for cornering
2) AGV length
3) Type of operations of AGV such as AGV carrying robot arms or an AGV carrying a payload is a critical parameter for the positioning accuracy
4) Maximum inclination
5) Irregularities of operation floor that can cause vibration.
6) Minimum required AGV speed during cornering
7) The selected motor and inverter combination should produce the required torque at the requested minimum speed operation. The second issue is the motor position accuracy at the requested minimum speed.
8) If required, design of suspension for each wheel
9) Physical dimensions and available space for the selected topology

In [25], AGV topologies shown in Fig.3 is studied considering three design parameters: maneuverability, stability, and controllability. As stated in [25], in order to maintain AGV stability at least three wheels should be in ground contact. Four and more wheels can improve stability and in this case flexible suspension system is required in order to maintain contact of each wheel to the ground [25].

In [26], AGV suspension design is studied. A suspension system acts as a mechanical filter and maintains the stability of AGV [26].

The suspension also provides mechanical protection to the motor and its bearings against vibration at imperfect floors.

Based on the evaluation of these topologies, the decision can be given to use the steerable drive, differential drive or Omnidirectional system. Steered drive includes the motor, inverter, gearbox of traction system and steering mechanism driven by a separate motor and inverter as well.

The type of vehicle wheel and wheel material should also be selected in conjunction with the traction topology. For example, in Omnidirectional AGVs, Swedish type or Mecanum type wheels provide an extra degree of mobility with respect to conventional rolling wheels. An AGV design example with Mecanum wheels is given in [27] **.** On the other hand, polyurethane wheels are primarily used in steerable and differentially controlled AGVs because of their advantages such as noise reduction, load-bearing capability, improved traction properties and resistance to corrosion [28]. Detailed datasheets are available in [28-30].

The design of Omnidirectional AGVs has been studied in [31-35].The steerable wheel has a rotating mechanism, including the traction motor and gearbox. Based on the received position reference, steerable wheel system can change its steering angle actively. Omni-directional wheels use a special wheel structure for movement in any direction. Swedish type wheels have been widely used in narrow maneuvers. Robot soccers is one of the typical applications [31].

In [33-34], a novel MY3 type wheel is developed. MY3 wheel is insensitive to dirt and any particles on the floor in any production environment. In [35], Omnidirectional AGV having 740 kg payload and driven by Mecanum wheels has been studied, including the design details such as finite element analysis, calculation of radial forces, mecanum wheel design, motor sizing, electric schematics and test bench. Design schematics in [35] indicate that an additional ball bearing and coupling are installed between gearbox and wheel are mounted for each wheel. In case the radial force limits of motor and gearbox per wheel can not handle the design limits, an external bearing system can be designed as shown in [35].Therefore, radial force limits of motor, gearbox and wheel should be analyzed in detail in datasheets. Assuming an equal distribution of total force per wheel, basic calculation of radial force per wheel is given as

$$F_{rad} = m/(N_{dr} + N_s) \quad (1)$$
$$m = (m_p + m_{agv})$$

Where: F_{rad} : is the radial force per wheel [N];
m : total weight of AGV including payload
m_p : payload [kg]
m_{agv} : mass of AGV [kg]
N_{dr} : number of the motor driven wheels [-]
N_s : number of supporting wheels [-]

However, this calculation assumes that all of the wheels are always in contact with the ground. In case of irregularities on the floor, one wheel may not be in contact with the floor. In this case, the radial force per wheel will be higher than the calculated radial force in (1). Such worst cases should be included in the calculations.

4.2. Motion control loops in an AGV

As depicted in Fig.4, AGV system controller calculates the position reference based on the target trajectory planning algorithm (TPA). Inverters (motor controllers) run in speed control mode following the output of the TPA. Similar control configuration is also studied in [27,36-37].

Motion control accuracy is very much dependent on the odometry system and its accuracy. Odometry is the calculation method of relative position of AGV. Odometry errors are due to the changes of the wheel elasticity at load variation and wheel slip.

In [38], it is proposed that encoder mounted on the non-driven wheel axle can eliminate errors caused by the wheel slip while applying the braking or driving torque by the motor. Odometry errors and solution proposals are studied in detail in [38].

4.3. Definition of specifications of AGV traction system components

Basic components of the traction torque are acceleration, friction and inclination torques as expressed by equation 2,3,4 respectively.

A template for motor sizing of an AGV are given [39-40]. In addition to the calculation methods in [39-40], RMS (root mean square) torque over a given period of operation should also be calculated to verify that RMS torque representing the load torque is equal to or less than the rated torque [41].

RMS torque can be calculated as given in equation (6). A detailed motor datasheet is available in [42].

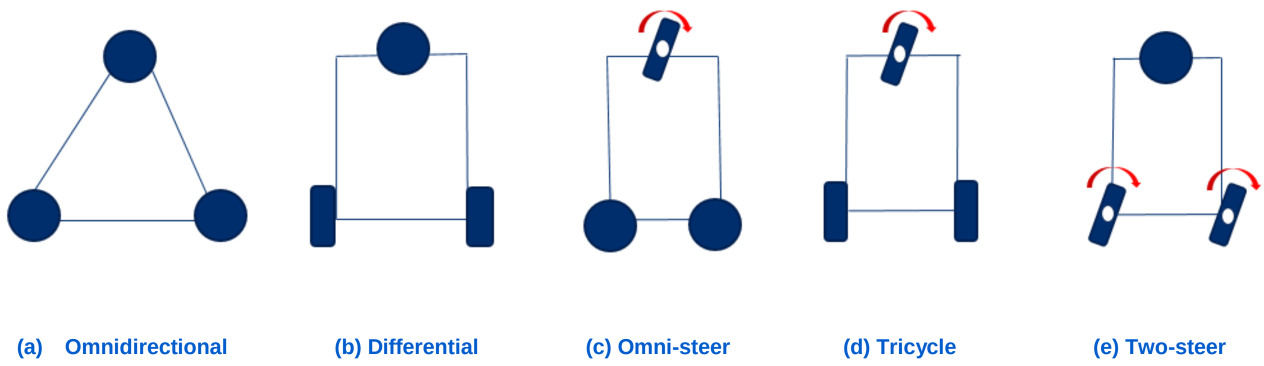

Figure 3. AGV traction system topologies [25]

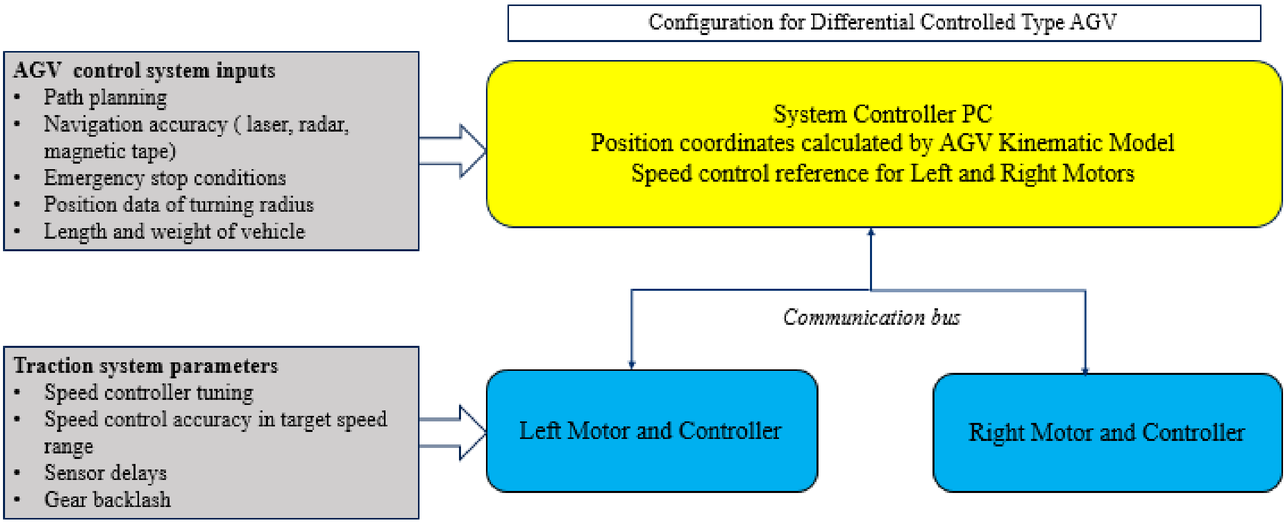

Figure 4. Basic schematics of AGV motion control and critical system parameters

$$M_{acc} = m\frac{dV}{dt}. \quad (2)$$

$$M_{rr} = mgf_r. \quad (3)$$

$$M_{gr} = mgsin(\theta). \quad (4)$$

$$M_{tract} = M_{acc} + M_{rr} + M_{gr}. \quad (5)$$

$$M_{rms} = \sqrt{\frac{M_1^2 t_1 + M_2^2 t_2 + M_3^2 t_3 + M_4^2 t_4 + M_5^2 t_5}{t_1 + t_2 + t_3 + t_4 + t_5}}. \quad (6)$$

m is the total weight of AGV as given in (1) ,f_r is the rolling friction coefficient of the AGV wheels, and θ is the inclination angle of the operation floor.

In fig.5, change of traction torque is given for an example duty cycle. It is assumed that AGV operates based on the operations as described below:

M_1: Acceleration torque at maximum payload.

M_2: Torque at constant speed operation. Payload is maximum.

M_3: Deceleration torque to lower speed.

(short resting period can be applied at the end of t_3)

M_4: Acceleration torque at reduced payload.

M_5: Torque at constant speed operation at reduced payload.

Durations of operations for each of the torques M_1, M_2, M_3, M_4, M_5 corresponds to t_1, t_2, t_3, t_4, t_5 respectively.

A sample duty cycle of AGV can be recorded during a test operation including the frequent start-stop operations at peak loads and possible inclination angles. Recorded duty cycle can be used for calculation of RMS torque.

Most of the motor and inverter suppliers have available products designed for 48 V DC input.

PWM frequency of inverters used in AGVs can be in the range of 12-24 kHz. Higher PWM frequency, in principle, increases inverter switching losses and motor core losses as well. Therefore, combined efficiency of the motor and inverter is necessary for energy consumption and energy management as well.

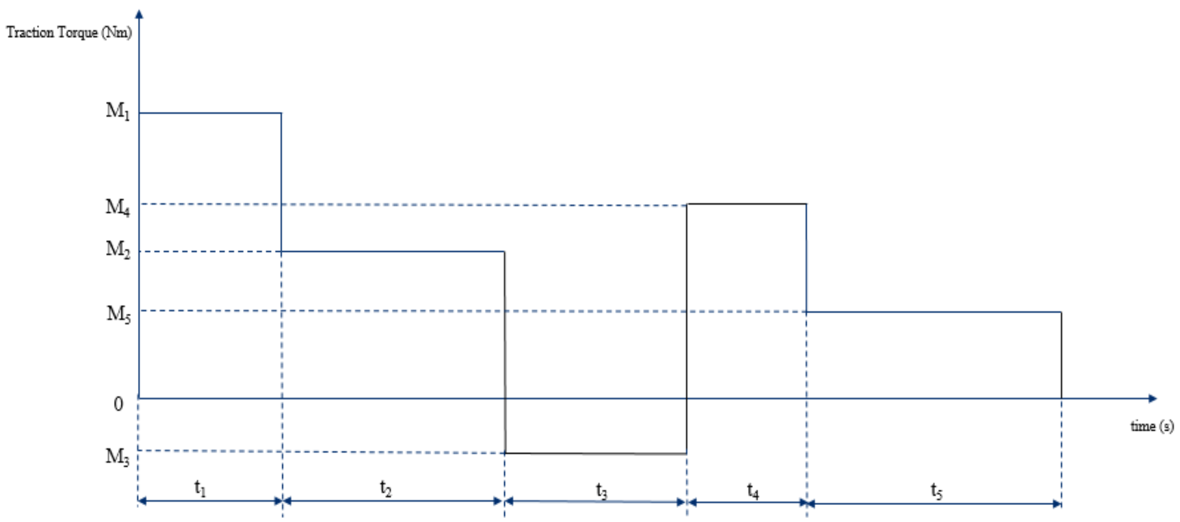

Figure 5. An AGV duty cycle example for RMS torque calculation

In case of a combination of motor and inverter from different suppliers, a combined efficiency map of motor and inverter can be derived by performing an efficiency test on a dynamometer test bench. In this way, efficient operation points on the motor efficiency map can be chosen for the target duty cycle.

Important details on component selection and application of AGV traction system are summarized below:

Inverter

- Speed control performance, available peak torque and speed accuracy below 200 rpm should fulfil the low speed AGV performance requirements (i.e. Vx < 0.1m/s) at maximum loads.
- The setting of the S-ramp profile in the inverter enables smooth start and stop, and can improve the positioning accuracy during stops.
- Safe torque OFF function, compliance with safety standards EN61800-5-2, PL e CAT3 EN ISO 13849-1:2015, SIL3 EN 61800-5-2:2017 [43].
- Use of brake resistors at the DC input terminals of the inverters provides overvoltage protection of battery and inverter in case of rapid deceleration and emergency stop conditions at maximum payloads.

Motor

- Cogging torque in permanent magnet motors causes speed and torque ripples, especially at speeds below 200 rpm. Cogging torque should be minimum in order to improve the AGV positioning accuracy [44].
- Maximum requested torque at the maximum ambient temperature should be verified by the motor datasheets.
- Efficient motor operation will reduce the motor thermal load, and provide longer duration of operation due to the efficient use of the battery energy. Efficient operation of the motor can be realized if the combination of gear ratio and motor speed reference yields an efficient operation point on the motor efficiency map.

Speed ranges between 0-300 rpm is typically not an efficient operating point for a motor having 3000 rpm rated speed.

Motor and Gearbox

- Radial force limit (RFL) at maximum load is the critical mechanical limits the maximum payload capacity. RFL is also a critical regarding the lifetime of motor bearings and gearbox.

Gearbox

- Lower backlash reduces positioning errors.
- Higher gear ratios reduces the load inertia reflected at the motor shaft, and hence enables easier tuning of the speed controller of the inverter.
- For the same power requirement, choosing a high gear ratio enables shifting the motor's operating point to the high-efficiency region, which can be greater than 85 % and energy saving as well.

Battery

When operating at maximum levels of inclination, operation at maximums of speed, load, and acceleration should be avoided. Because this is the worst case for the energy consumption and causes rapid discharge of the battery.

5. INTEGRATION AND APPLICATION ASPECTS OF AGV TRACTION SYSTEM

5.1. Preventive measures against the failure of AGV traction motors

AGV is an enclosed vehicle without any airflow inside. Most of the traction motors of AGVs are naturally cooled and can be exposed to overload cyclically because the operator can exceed the payload limits. If the specifications at conceptual development does not consider real-life operation conditions, motor premature failures such as winding and bearing failures can occur. As a consequence of this, undesired shutdown can occur.

Due to the lack of studies on motor and inverter failures specific to the AGV applications, relevant studies from industrial and electric vehicle applications are reviewed which can provide also input to the AGV applications.

In order to prevent component failures, as a general rule, the unsymmetrical distribution of payload placed on AGV should be avoided as it can cause electrical and mechanical overloading of motors and gearboxes either on left or right side of AGV. It can also cause exceeding the radial force limits of bearings and gearboxes.

In [45], it is stated that thermal stresses, mechanical vibrations and humidity are the first three causes of inverter failures caused by long-term wear-out. Inverter manufacturer's test conditions in the production phase may not match the field operation. Considering the cyclic overload conditions, ambient temperature variations, and mechanical vibrations due to the floor imperfections, inverters used in AGVs can easily be exposed to the failure risks analyzed in [45].

In order to prevent failure of AGV during the operation, a list of possible motor failures are briefly given here, and possible solutions are discussed. Most typical motor faults occur in stator, rotor and bearings. Common stator faults are due to thermal overload or short circuited turns inside the stator windings. Bearing faults can be caused by thermal overload, mechanical overload, and shaft misalignment. In induction motors, broken rotor bar failures can occur due to prolonged and frequent acceleration at high torque applications.The causes of motor failures and solutions are studied in [46-50].

These problems have a slowly progressing nature, and therefore may not activate a protection function instantly. However, they can cause instant failure anytime, which can cause production stops. In [47], it is stated that almost 50 % of all motor failures are related to mechanical faults. Electrical faults of the motors can also increase noise and vibration. Consequently, noise, vibrations, and finally, the total damage to the machine and the mechanics can occur if the failure is not detected and isolated.

The list of proposed preventive measures are given below:

- Road imperfections should not cause violation of permissible vibration at the motor shafts and gearboxes. Suspension design can be considered as a solution.
- The inverter's current and torque limits should be set to limit the requested maximum torque, protecting the motor against overloading.
- In order to prevent any premature failure and detect the design problems at the earlier stage, AGV motors, bearings and gearbox should be tested periodically. Tests can be categorized as electrical faults and mechanical noises from shafts, bearings and gearboxes. Motor condition monitoring modules available in the market are not cost-effective for an AGV. An alternative solution can be use of motor and inverter test equipment [51] for periodic diagnosis.

Thermal failure risks of AGV traction motors and inverters

- Frequent acceleration at maximum payload.
- Limited resting period for cooling of the motor and inverter.
- For under-drive type AGVs, payload between left and right motors should be symmetrically placed. Otherwise, overheating risks of motor and inverter can also occur.
- Exceeding the RMS torque limits during the operation periods.

Proposed practical solutions

- Use of motor temperature sensor. Statistical evaluation of motor temperature sensor to track the overheating risks through the operations.
- Periodical temperature measurement of motor and inverters by thermal camera.
- Correct settings of current and torque limits for the inverters.
- Comparing RMS motor currents and motor temperature of all traction motors installed on left and right side of AGV for a given duty cycle. This can be helpful to evaluate the load share between left and right side motors.

5.2. Energy-Efficient Operation of AGV

Electrical supply of AGVs up to 3000 kg payload are typically lithium-based batteries. However, energy storage of heavier AGVs (> 3000 kg) can be designed as hybrid systems such as battery and supercapacitor, or fuel cell and ultracapacitors [52]. Energy management of an AGV is required to predict if the next operation can be completed with the available battery energy.

The tasks of energy management and efficiency optimization of an AGV can be categorized into six different levels, covering the software development at a higher level and optimizing the component specifications and efficient operation of the traction system at the lower level. A summary from the state of the art is given below:

1) Energy consumption and prediction models for a given load and speed profile: In [52], variation of power and SOC of the AGV energy storage system is simulated for different operation conditions.

2) *Path planning minimizing the distance*: In [53], using the linearized AGV model, path planning control is implemented using the constraint of minimum energy consumption.

3) Energy-efficient design of traction system considering the most efficient operating points: Detailed analysis of power and energy consumption of AGV is studied in [54-55]. In [54], it is reported that the higher AGV speeds yield higher efficiency and less battery energy consumption. This is due to the operation of motors at higher efficiency points. On the other hand, in [55], 2 m/s AGV speed yields rather higher energy consumption such as 0.423 kWh whereas reducing the AGV speeds to 0.7 m/s reduces the energy consumption to 0.305 kWh in one of the test cases. One reason can be increase of friction of mechanical components at higher AGV speeds. Complete model on losses of mechanical and electrical components and efficiency map of traction system is required for evaluation of energy efficiency measurements of AGVs.

4) *Flux optimized induction motor control:* Optimized flux operation of an induction motor at no-load and partial load of AGV can be potentially effective function for energy saving. This function is available in industrial applications like pumps and HVAC and it stills needs to be developed for AGV inverters. In [56], the flux-optimized induction motor is studied for an electric vehicle.

5) Utilization of regenerative energy: Regeneration can occur mostly while decelerating from high speed (i.e. from

2000 rpm motor speed) to standstill or low speed (i.e. 200 rpm range). In order to utilize the benefits of regeneration, AGV duty cycle can be planned to operate at high speed range.

6) *Optimization of operation variables by data analytic tools:* Operation variables involving in energy consumption can be optimized using the data analytic tools as given in [57]. These variables can be AGV speed, path plan, acceleration time, maximum load, periods and speed of charging time.

In Fig.6 and Fig.7, power and energy consumption from the battery terminals of an AGV used in automotive production has been given at 0.087 m/s, 0.174 m/s, 0.349 m/s, 0.698 m/s longitudinal vehicle speeds for 10 m distance for each speed. Tests are performed without any payload. The results are in parallel to the results reported in [54]. Energy consumption of an AGV is higher at lower speeds and lower at higher speeds for the same distance. Because, motor efficiency is increasing as the speed goes higher.

Best efficiency can be around 96% for permanent magnet synchronous motors.

In case of an energy efficient control of an AGV, energy management software module can select the speed which can yield most efficient point corresponding to the actual payload.

6. ELECTRICAL SYSTEM DESIGN OF AGV

AGV inverters operate at high PWM switching frequency (12 kHz-24 kHz range) and high current ratings (ranging from 50 A up to 450 A peak motor currents) at 48 V DC input. High current power cables and low current signal cables and sensors are installed in the same limited space in an AGV. Therefore, it is critical to apply all basic EMC /EMI design rules. EMC guidelines are given in [58-59]. Shielding of power and signal cables and minimizing the length of the cables between the battery and inverters are the basic and critical rules.

Operation of inverters at high PWM frequency and at high current can increase the risk of interference to signal cables of system controller, PLC and sensors. EMC/EMI issues should be considered during the layout design and can be minimized by performing a precompliance test during the prototype phases. In this way, on-going problems can be detected at the earlier phases of the development.

6.1. EMC compliance of an AGV

EMC test compliance of all electrical components referring to the EN 61000-6-4 standard should be verified at the design phase. A list of EMC and machine safety standards for AGV is given in [60].

Charger should unit should fulfil the conducted emission standard for the grid.

When the AGV fleet operates in a given zone, each AGV can radiate noise to each other and other electrical components in the same operating zone. In [21,61], analysis and solutions are studied for battery electric vehicles considering the EMI (electromagnetic interference) risks in traffic, which also provides inputs for EMC/EMI issues of AGVs.

The root causes of EMI problems in electric vehicles are the same in AGVs as power electronics components can cause interference to the electronic control modules and sensors inside AGV.

Component selection with the relevant EMC certificates and design and layout of electrical cabling considering basic EMC rules should be included in the conceptual development phase.

6.2 Common mode currents in AGV motor and inverter

In this section, possible interactions between common mode currents created by inverter and EMC/EMI related problems of an AGV is discussed briefly. Common mode currents (CMC) induced by common-mode voltages of inverter and its effect on bearing failures have been studied extensively in industrial applications and recently realized as a design and application problem in electric vehicles [62-71].

CMC currents flowing through the motor bearings are also called as bearing currents.

Schematics given in [62] can be used to analyze the problem for an AGV as well.

As stated in [62], some part of CMC can follow a return path to the inverter through the vehicle body causing large EMI problems. Same risks are valid for AGVs. Moreover, AGVs can have two, four or six motors which can amplify the EMI problems. Considering the high frequency content of CMCs, it can increase the interference risks to the AGVs nearby and electrical equipments inside and outside of AGV.

Unlike an electric vehicle, AGVs carry a payload based on their loading profile and bearings are exposed to load most of the time. Therefore, bearing currents caused by the inverter can potantially accelerate the failure of bearings in AGVs.

Further researches are needed to analyze the risks of bearing currents at 48 V operation and inverter PWM frequency range between 10 kHz-24 kHz.

A solution on the motor side is to apply specially designed insulated bearings [69]. Another solution is using a common mode filter that is not as effective as the insulated bearing; however, it can mitigate the problem. Measurement of shaft voltages by measurement instruments like in [51] is the practical way to evaluate the risks of bearing currents and potential EMI risks as well. Detailed analysis and solution proposals on CMC are studied in [62-71].

6.3. Electrical safety against electrical arc

It is known that 48 V systems draw a higher current than 400 V supplied electrical systems at the same electrical power.

An electric arc can occur at voltages higher than 16 V DC [72]. Although 48 V is electrically safe to the human body,electrical arc in a broken cable or loose contacts can cause the burning of components and fire [72-75].

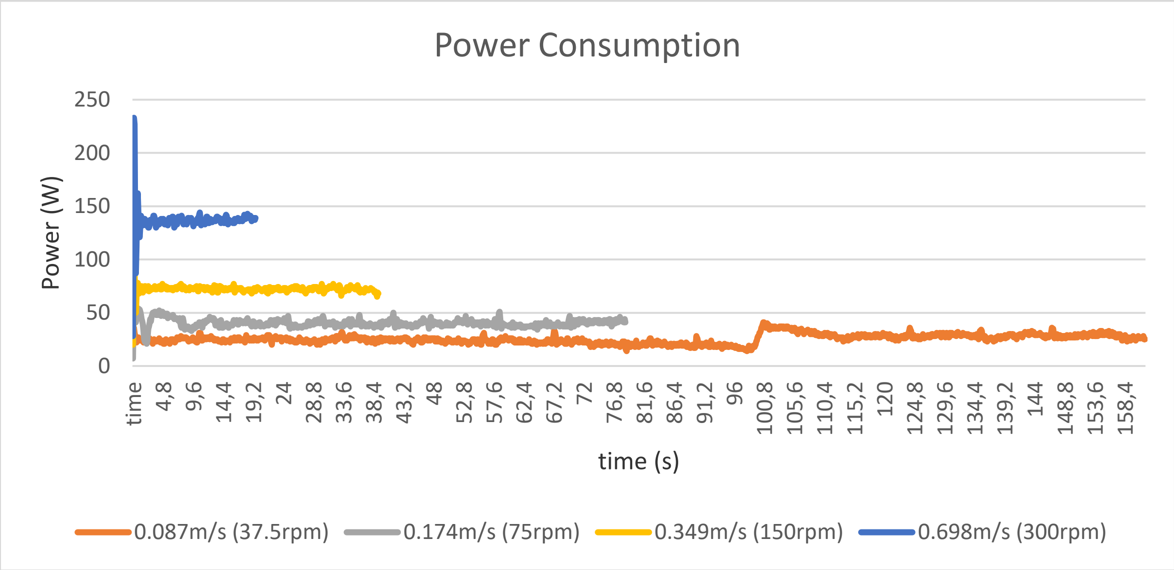

Figure 6. Electrical power consumption of an AGV at four different speeds. Payload is set to zero.

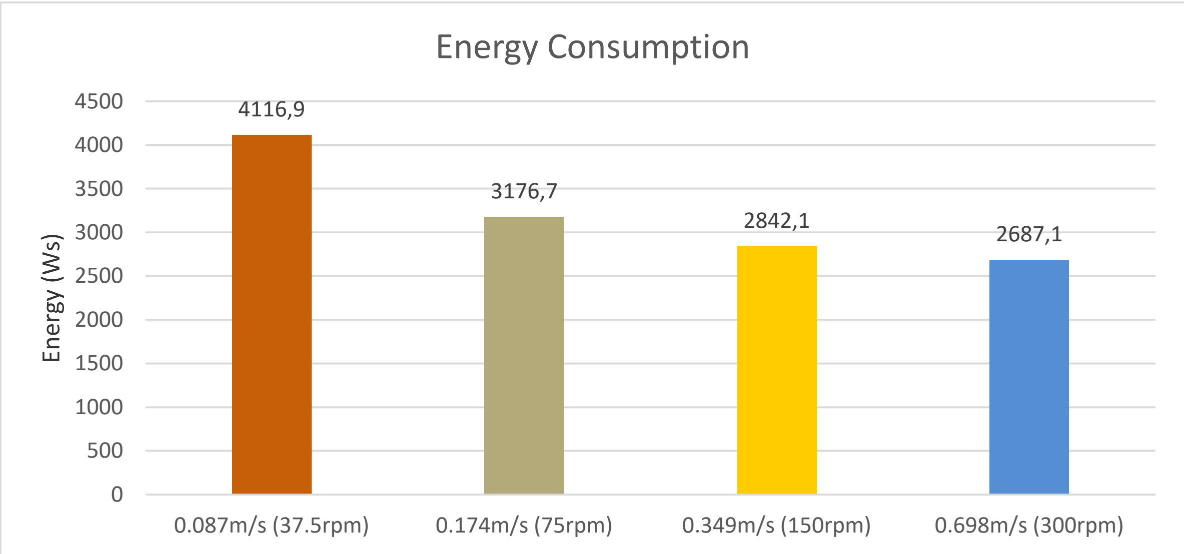

Figure 7. Energy consumption for the condition given in fig.6.

Due to exposure to vibration at surface imperfections, temperature variations, dust and humidity in the operation environment, electric arc due to the loose connections can occur inside AGV.

Therefore, any arc inside the AGV should be detected, and an emergency stop should be activated immediately.

In [75], arc occurrence and hazards in battery-supplied DC and AC supplied systems have been analyzed.

Occurance of an arc is a safety-critical situation considering the space limited layout of AGV components and lithium based batteries used as energy storage of AGV. Moreover, if AGV should carry a payload like a lithium battery in an electric vehicle production, electrical safety of the battery inside the AGV is even more critical.

As stated in [73], the consequences of an arcing short-circuit or earth-fault inside a low voltage panel can be very disastrous. The extremely hot electric arc can destroy valuable equipment causing prolonged and costly downtimes.

Protection solution for 48 V automotive systems is given in [72].

Arc flash detectors in medium and low-voltage switchgear systems given in [74,76] can be also used in AGVs designed at high power levels. Because the arc flash sensors operate based on the light occurred by the arc.

6.4. Regeneration and use of brake resistor

AGV traction system can regenerate when decelerating from maximum speed to standstill or low speeds.

Inverter overvoltage failure can occur in case of rapid deceleration or emergency stops at maximum payload condition.

A brake resistor connected to the DC input terminals of inverter can protect the battery and inverter against overvoltage.

Detailed electrical design guidelines for an AGV motor-inverter application can also be found in [77].

7. FUTURE TRENDS FOR AGV TRACTION MOTOR AND INVERTERS

Estimated future trends for the optimized AGV traction system are summarized below:

1) *Integrated motor and inverters*

The availability of integrated motors and inverters (IMI) are limited for AGVs. However, the IMI provides tested performance and preset tuning by the supplier. As the cable between the motor and inverter is eliminated, IMI can mitigate dV/dt voltage stress at the stator terminals of the motor and reduce EMI problems as well. Because of the electrical benefits and compact dimensions of IMIs, AGV applications need IMI solutions.

2) *48 V Induction motor as an alternative to PM motor:*

Due to the rapid growth of electromobility and AGV market, supply problems and price increase of rare earth elements has been discussed more than a decade and problem will be even more dramatic as the market for AGV and electromobility applications grow very fast.
Induction motors are the best alternative to permanent magnet synchronous motors (PMSM) in AGV applications both technically and for cost reduction purposes. There are 48 V induction motor solutions in the market for AGVs [24,78].

3) *48 V Induction motor drives with optimized flux control at light loads:*

For pump and HVAC loads, this function is available in industrial induction motor drives [79]. Basic principle is to optimize the induction motor efficiency by optimizing the motor flux and minimizing the motor losses at light loads. This function is currently at the research level for electric vehicles [56,80] and a research is not available on AGV. It is difficult to develop it in a battery electric vehicle where the drive cycle and inclination angle can be highly variable which means motor load is highly variable. AGVs operate at predetermined speeds and loads. Therefore, induction motor flux optimization can be adapted to AGVs easier than electric vehicle applications.

4) *Temperature related power derating:*

New thermal concepts are required to mitigate the thermal de-ratings of all power components at high ambient temperatures. On the other hand, minus temperatures will decrease available AGV battery capacity and hence reduce the payload capacity as well. Unlike an electric vehicle, AGVs do not have a cooling system for motors, inverters and batteries. Derating behavior of both induction motor and PM motor should be compared above 40 º for an AGV duty cycle in real conditions.

A possible remedy could be injecting cooled air into the motors by installing a cooling pipe when the AGV is parked while docking or charging. This will be a similar to plugging the charging cable of an electric vehicle during the parking. Extra housing is needed for the motors so that the cooled air will only be injected into the motor and will not cause an increase of humidity to the other electrical components inside the AGV.

At minus temperatures, payload capacity will be limited because of the limited battery discharge current. Therefore, temperature of the operation environment should comply with the allowable operation temperature of AGV battery.

Energy management strategies of an AGV has not been studied in detail in state of art. However, an energy management control module in AGV software, thermally optimized traction system and battery are mandatory for energy efficiency improvement at system level.

5) *SiC and GaN semiconductors:*

48 V supplied PM and induction motors and inverters are available at various current ranges [24,78,81].

SiC and GaN technology will enable thermal and efficiency improvements in inverter hardware. For example, Texas Instruments has developed a 48 V 10 A inverter with GaN (Gallium Nitride) transistors [82].

As stated in [82], advantages of GaN FET over Silicon FET can be described as having lower conduction losses, lower gate driver losses enabling faster switching, lower switching and conduction losses. All these improvements will increase the total system efficiency of the AGV.

Considering the demand for higher traction power for AGVs at 48 V, SiC and GaN technology is expected to be applied in AGVs in the near future.

6) *Motor control functions:*

- Motor parameter identification: Combinations from different motor and inverter suppliers can be implemented if motor electrical parameters can be identified by the inverter. This is not a common function in AGV inverter.
- Duty cycle estimation for a given AGV operation: Estimated motor shaft torque as a function of time can be logged in inverter. Based on the logged data, motor power sizing and RMS torque calculation can be done based on a defined duty cycle.
- Motor condition monitoring algorithms embedded in inverter can increase the reliability of AGV operation.

7) *Monitoring functions to support cyber security:*

- Suspicious and irregular acceleration patterns can be detected by tracking the motor current and speed by the inverter and reported to system operator. Emergency stop against a suspected cyber attack can be performed in such a case.

8) *Inverter communication interface:*

- ROS systems enables practical implementation of communication between the electronic modules. There is a growing need for ROS compatible inverters.
- In order to facilitate the system integration, AGV inverters should be designed to have optional communication interface modules supporting the most commonly used communication protocols such as Profinet, EtherCAT, CANopen, Modbus RTU, and USB.

 ISSN 2536-5010 | **e-ISSN** 2536-5134 https://dergipark.org.tr/en/pub/ejt

8. CONCLUSION

In this paper, the AGV traction system, critical development and integration parameters have been studied. It is concluded that all subsystems of an AGV have interaction with each other. Each phase of conceptual development has impact on performance of AGV in the operation environment. New generation AGV traction systems should be optimized for higher efficiency. Thermal optimization is also required for improvement of available motor power. Energy management algorithms should be developed specific to AGVs. Energy efficiency of AGVs at system level will be critical performance indicator for the plant's energy efficiency as well.

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